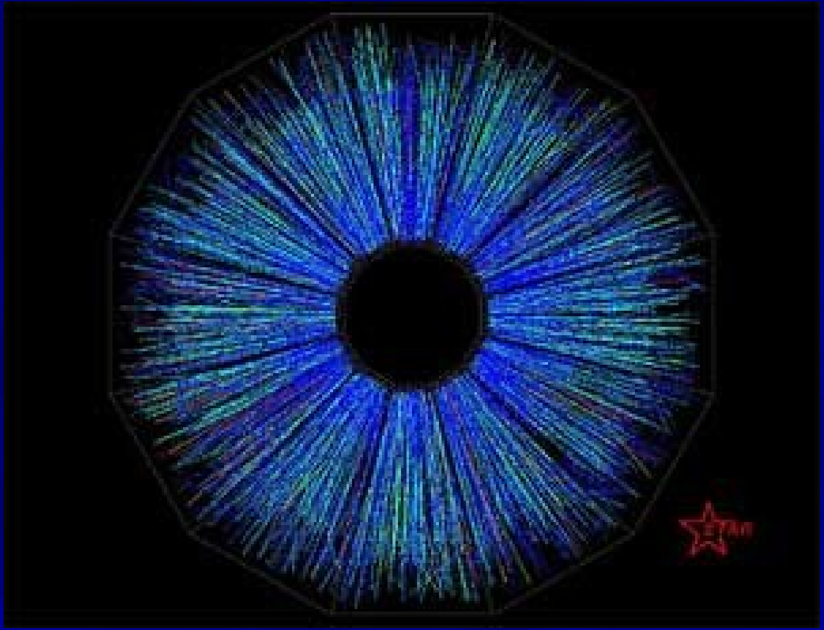
The perfect liquid and other highlights from RHIC



- Introduction to QCD and high energy heavy ion physics
- Soft/bulk results from the Relativistic Heavy Ion Collider
- Hard/Jets results from RHIC
  - Perspective for day 1 physics at LHC

The standard model particles and interactions

Matter particles
All ordinary particles belong to this group

These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators

	LEPTONS		QUARKS	
FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of -1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second	**Up** Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay	**Charm** A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1964
THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** not yet discovered but believed to exist	**Top** Heavier still	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

Force particles
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered

Gluons
Carriers of the strong force between quarks

Felt by:
quarks

The explosive release of nuclear energy is the result of the strong force

Photons
Particles that make up light; they carry the electromagnetic force

Felt by:
quarks and charged leptons

Electricity, magnetism and chemistry are all the results of electro-magnetic force

Intermediate vector bosons
Carriers of the weak force

Felt by:
quarks and leptons

Some forms of radio-activity are the result of the weak force

Gravitons
Carriers of gravity

Felt by:
all particles with mass

All the weight we experience is the result of the gravitational force

GRAPHICS: PETER CROWTHER

QCD and hadronic matter

3 color charges (red, green, blue)

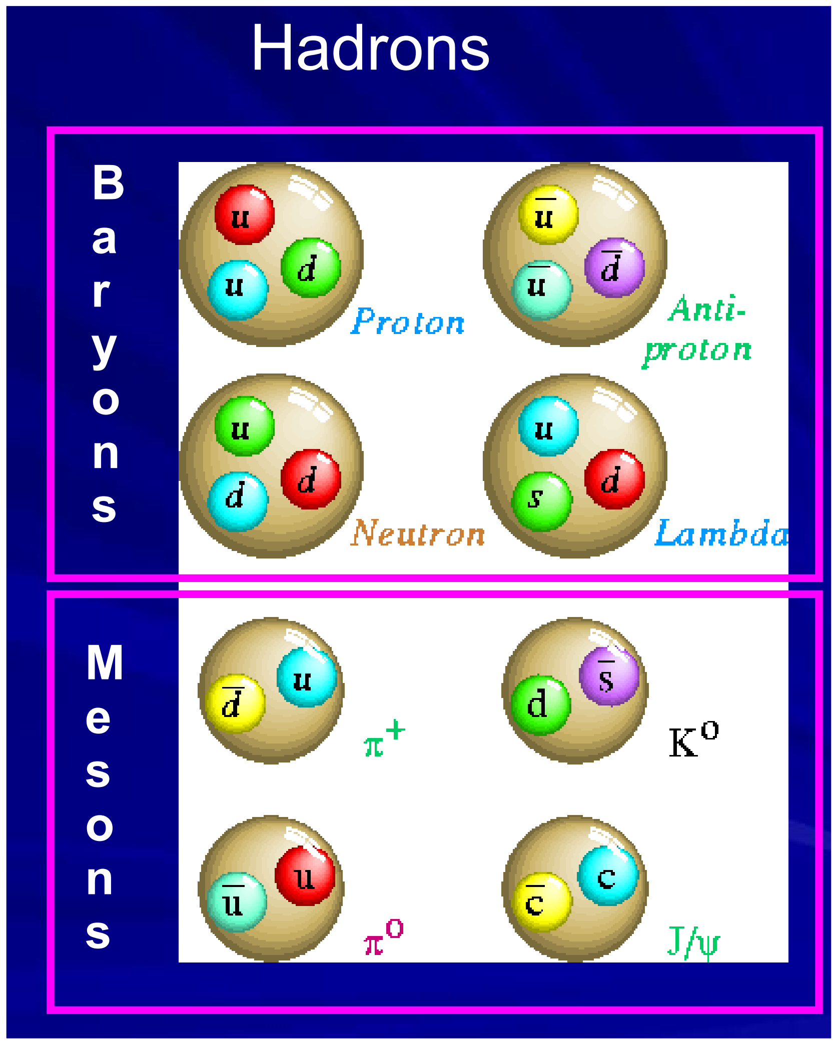
Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!

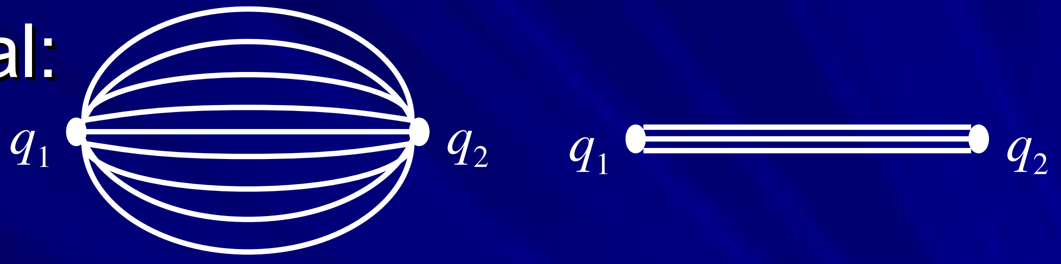


QCD Confinement and other Complications

- QED vs QCD potential:

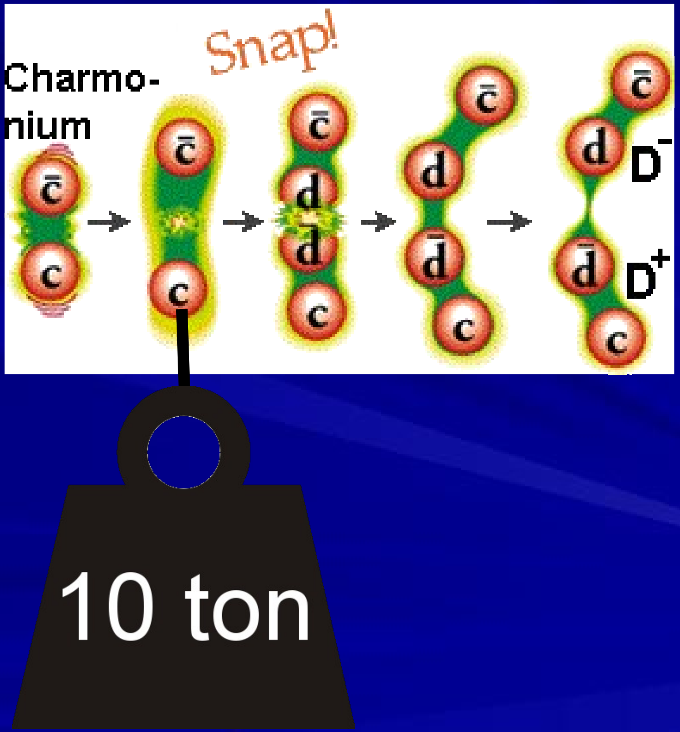
$$V_{em} = -\frac{c}{r} \qquad V_s = -\frac{c'}{r} + kr$$

c, c', k constants



a) QED or QCD ($r < 1$ fm) b) QCD ($r > 1$ fm)

- Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm
- QCD is for low energies non-perturbative $\alpha_s \sim 1$
  - We know the theory but we cannot solve it!
- But at high energies (small distances << 1 fm) we can use perturbative QCD

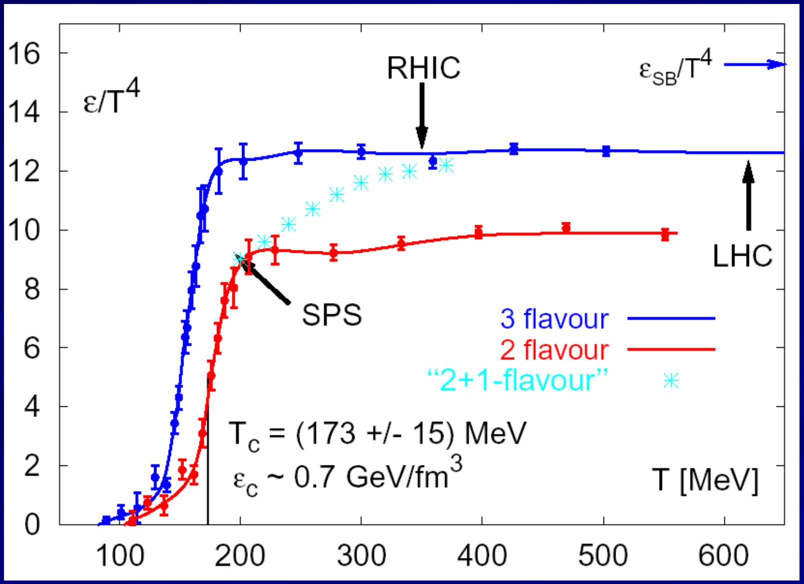


Numerical QCD at high temperatures: a gas of q and g

$$\epsilon_{QCD} = \frac{\pi^2}{٣٠}\left(2\times 8 + \frac{7}{٨}2\times 2\times 3\times 3\right)T^4$$

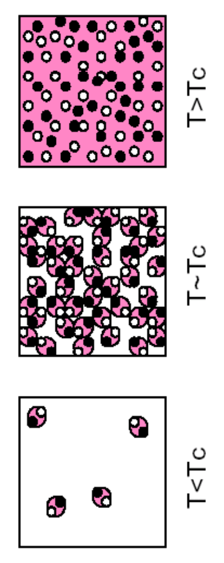
Gluon spin and color

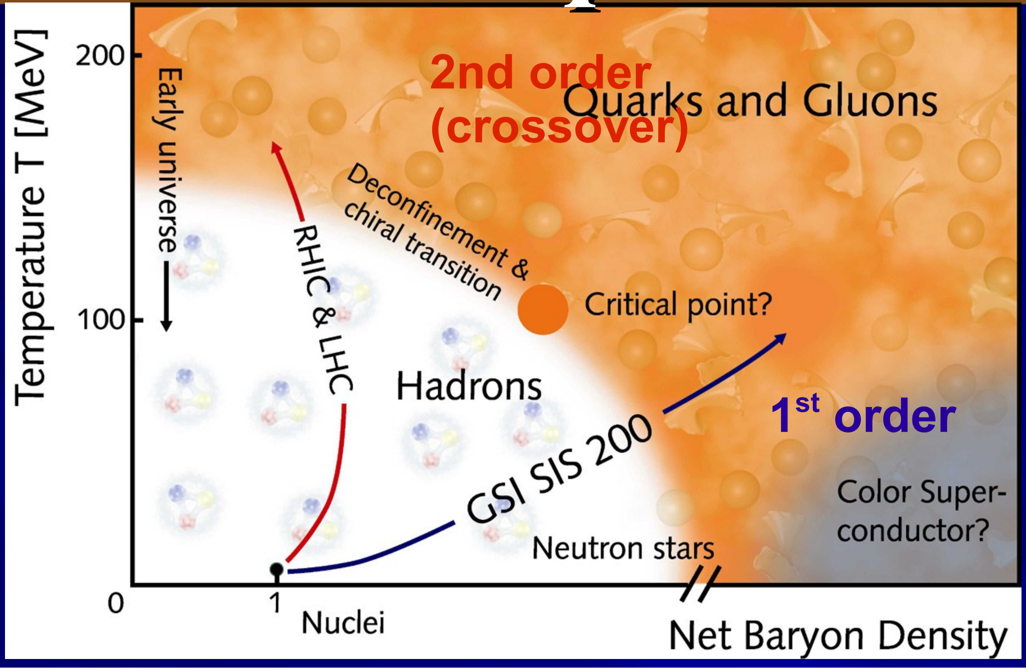
(Anti+)quark spin, color and flavor (u, d, and s)



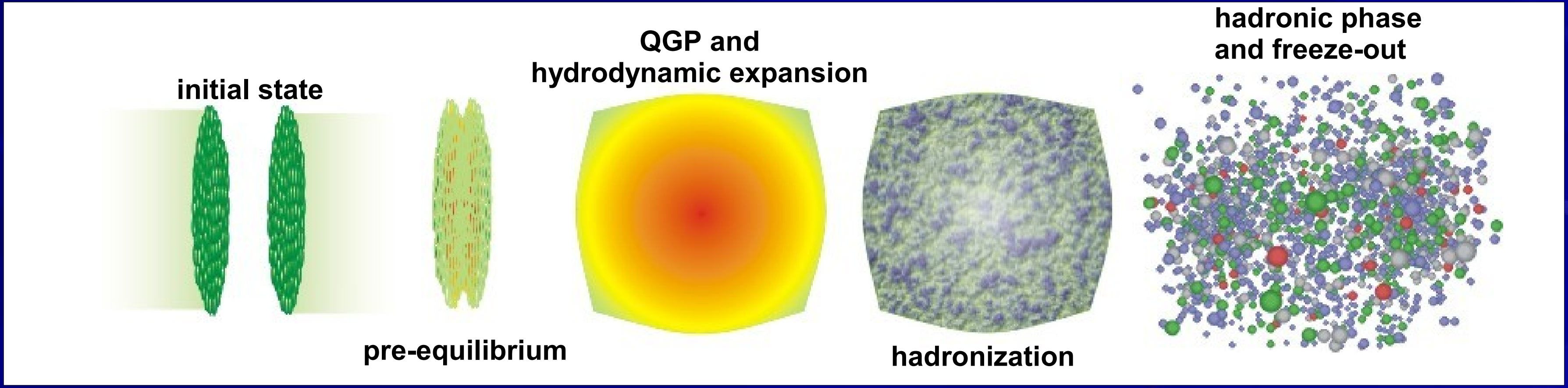
This suggests that the Quark Gluon Plasma should behave as a gas of quarks and gluons!

Deconfinement at large temperatures



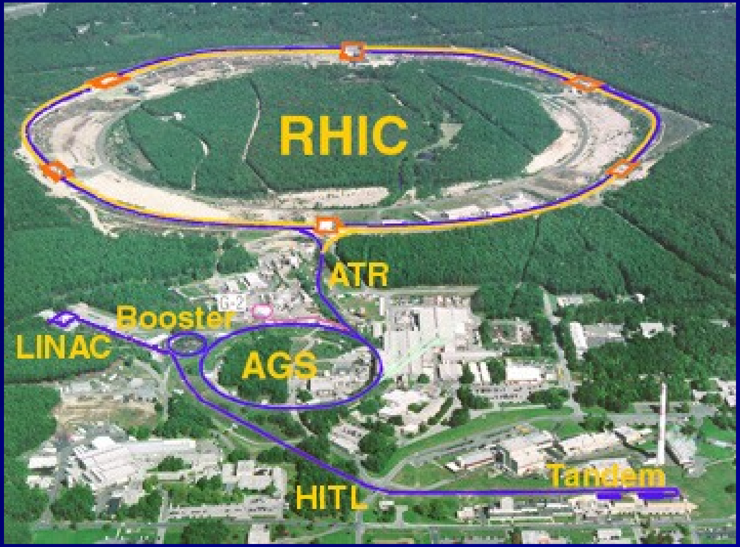


- At T>170MeV (ε>1GeV/fm^3) we expect a phase transition to a Quark Gluon Plasma (QGP)

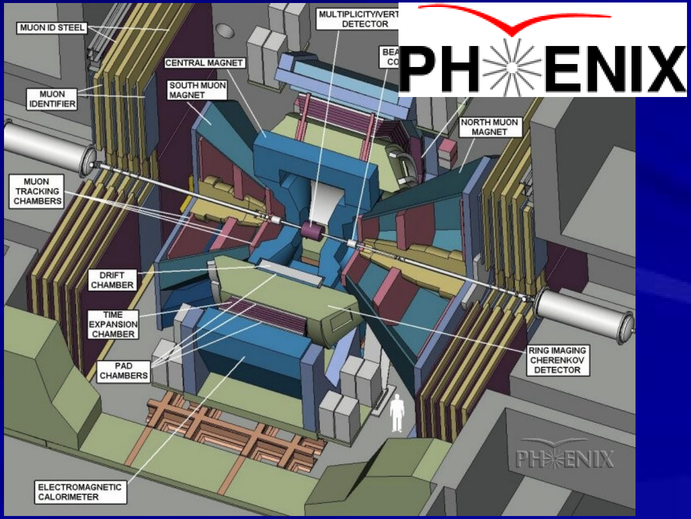


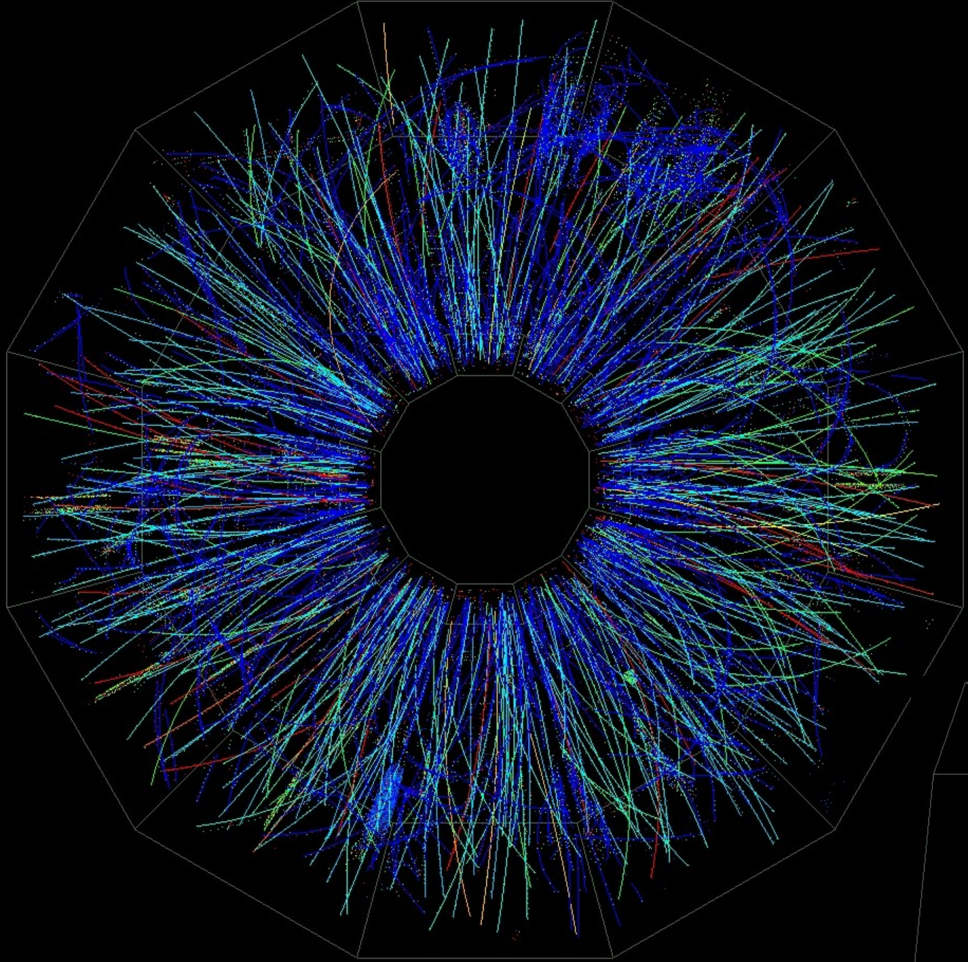
Current and future facilities

- Accelerators to produce the high energy beams
  - Relativistic Heavy Ion Collider at Brookhaven National Laboratory (outside new York)
  - Large Hadron Collider at CERN (near Geneva)



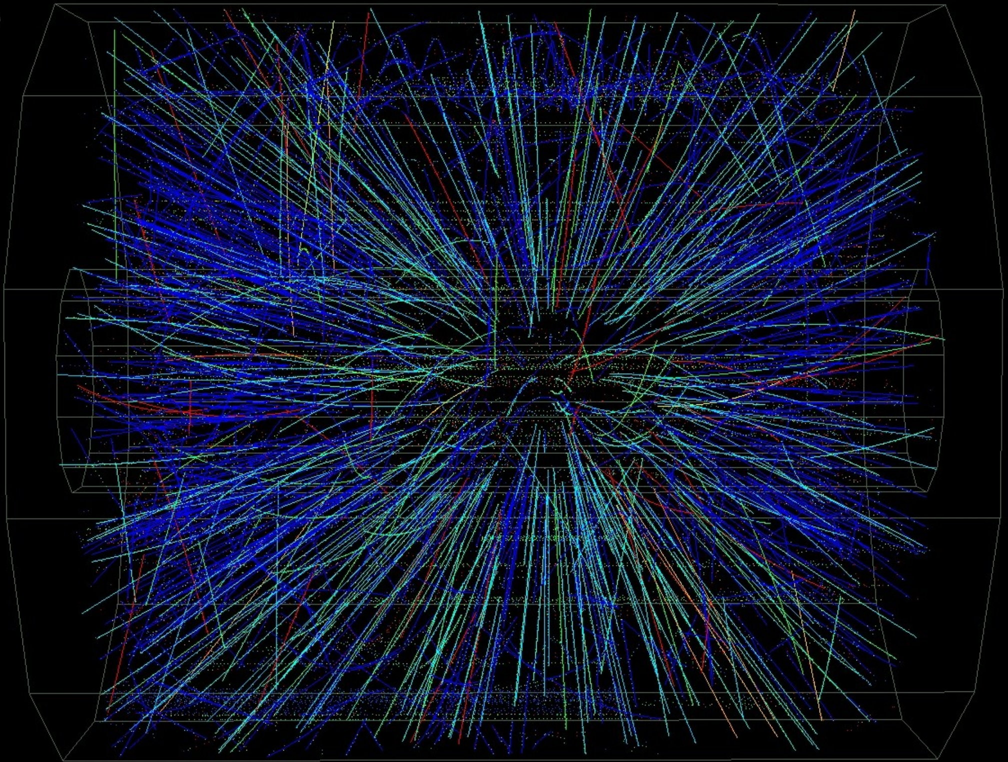
- Experiments to detect and reconstruct the final state particles
  - PHENIX and STAR at the Relativistic Heavy Ion Collider
  - ATLAS and ALICE at the Large Hadron Collide

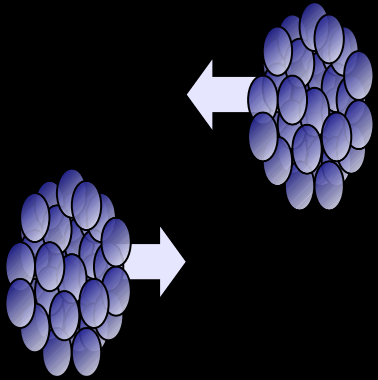


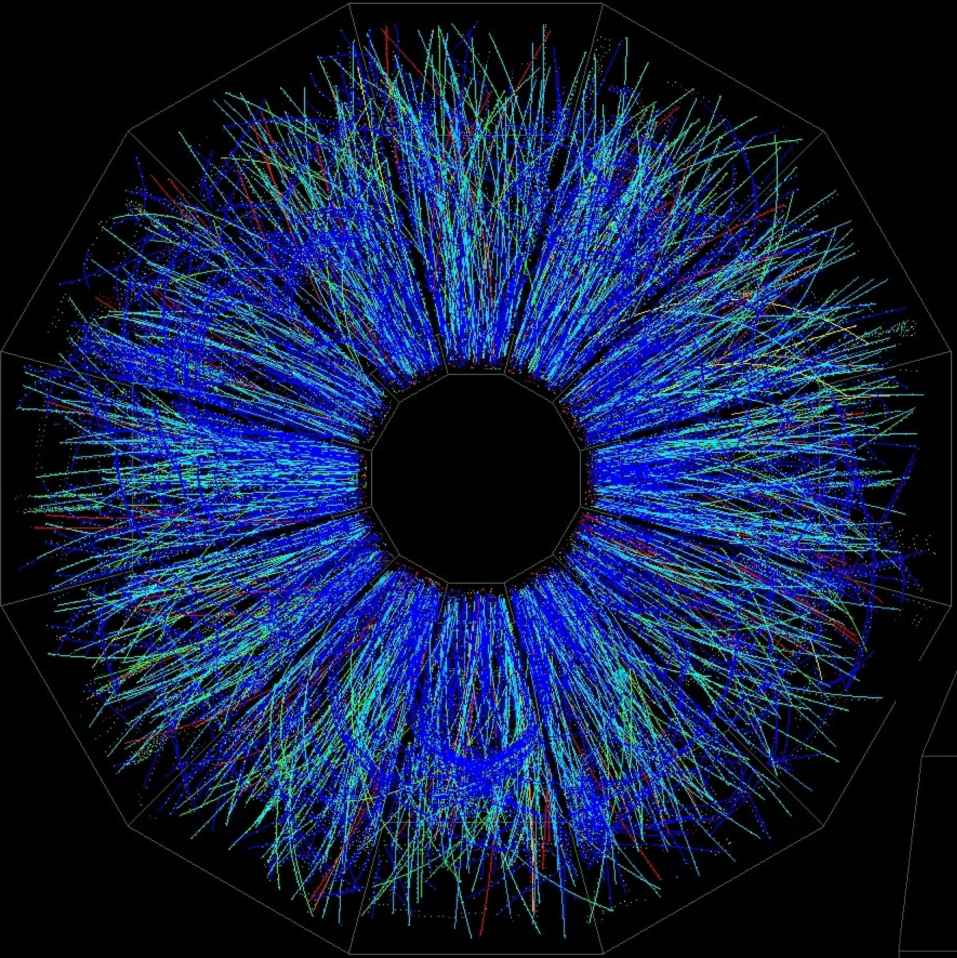


Peripheral Event

From real-time Level 3 display.

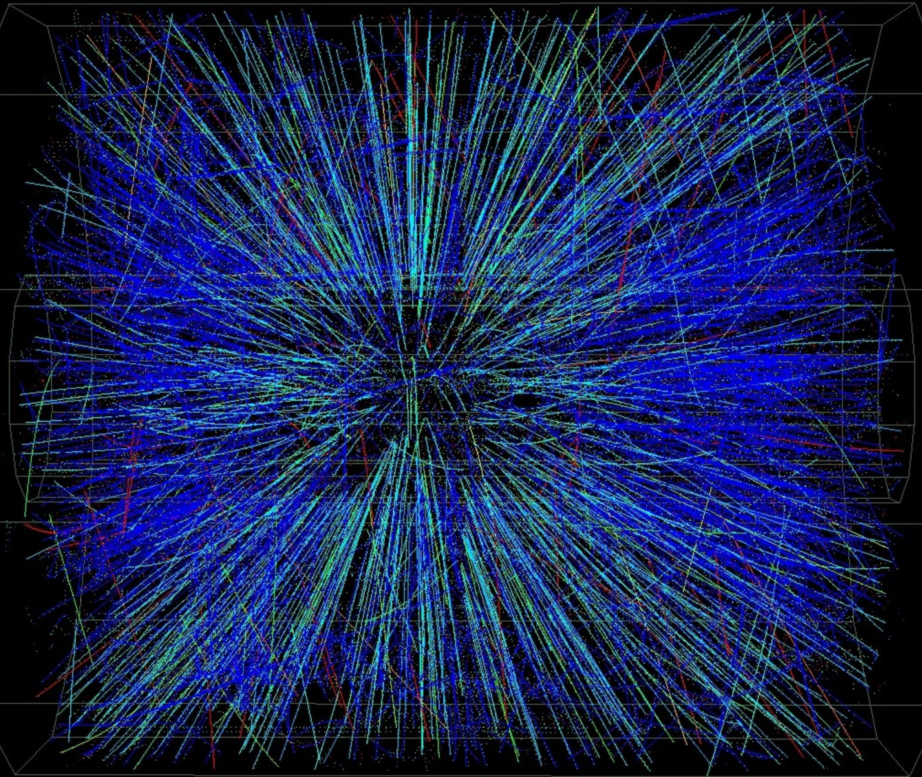


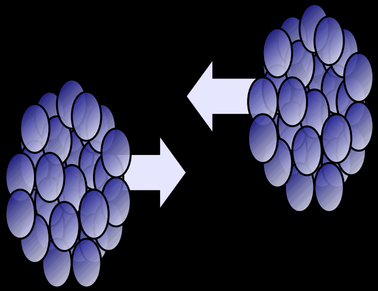


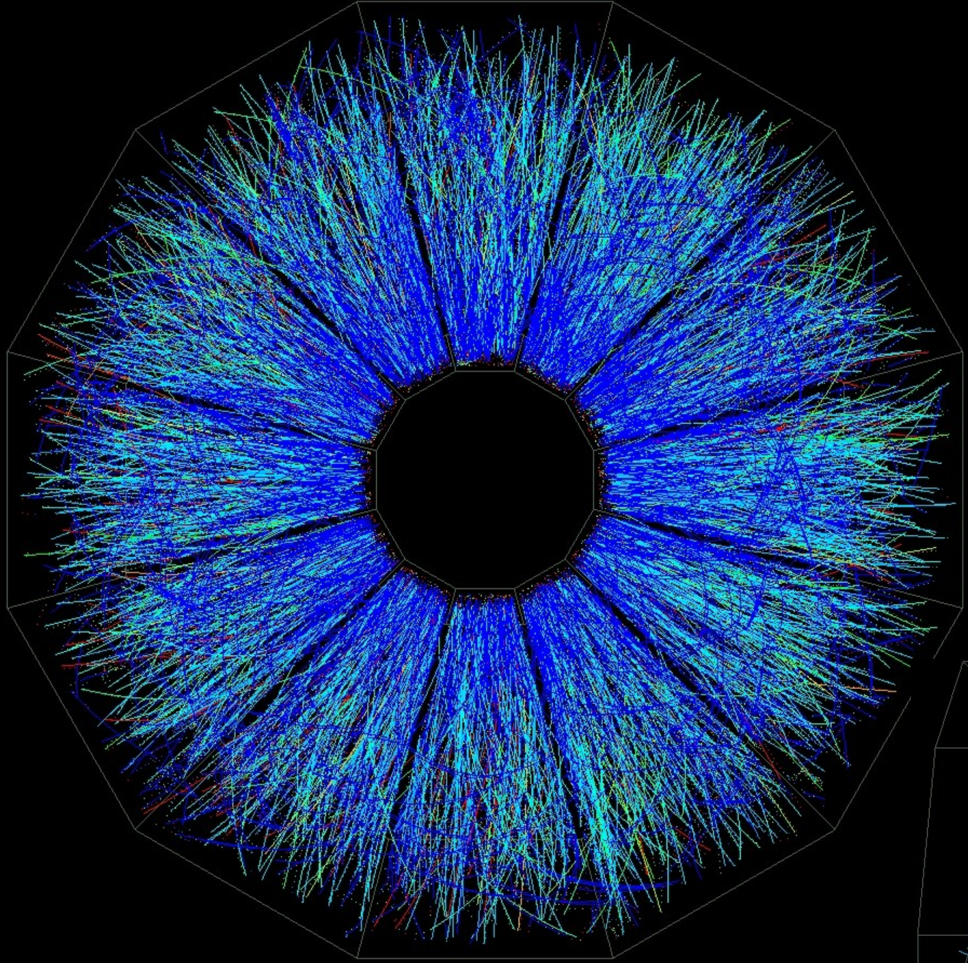


Mid-Central Event

From real-time Level 3 display.

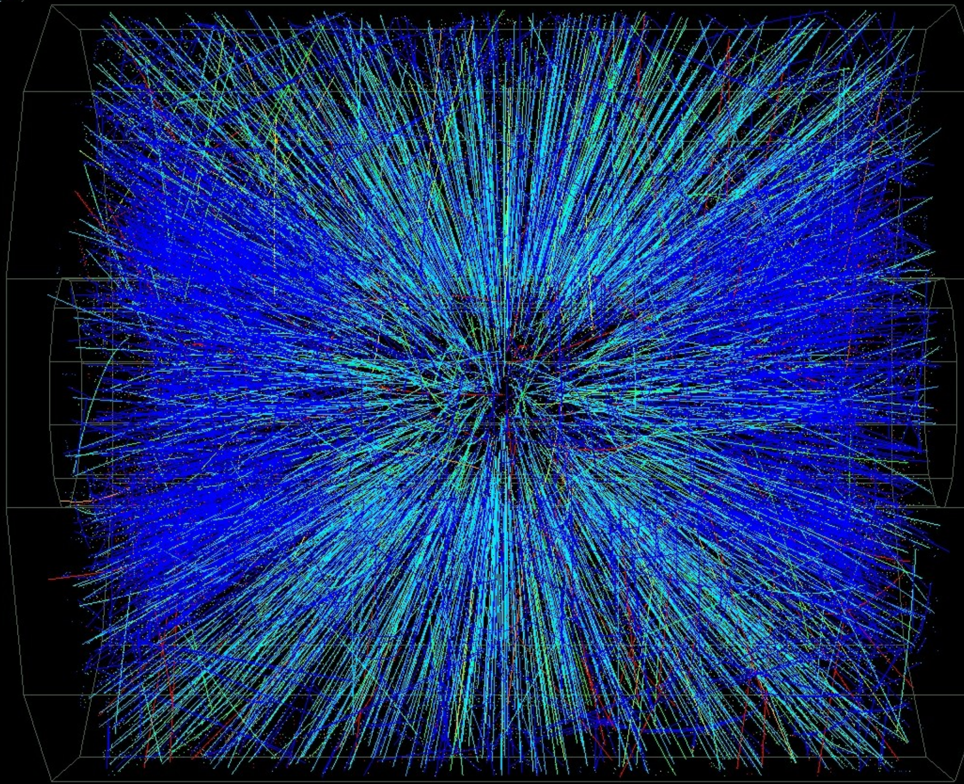


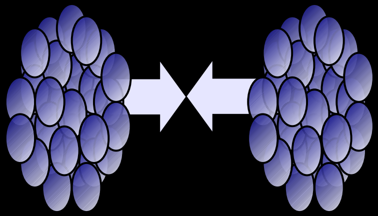




Central Event

From real-time Level 3 display.





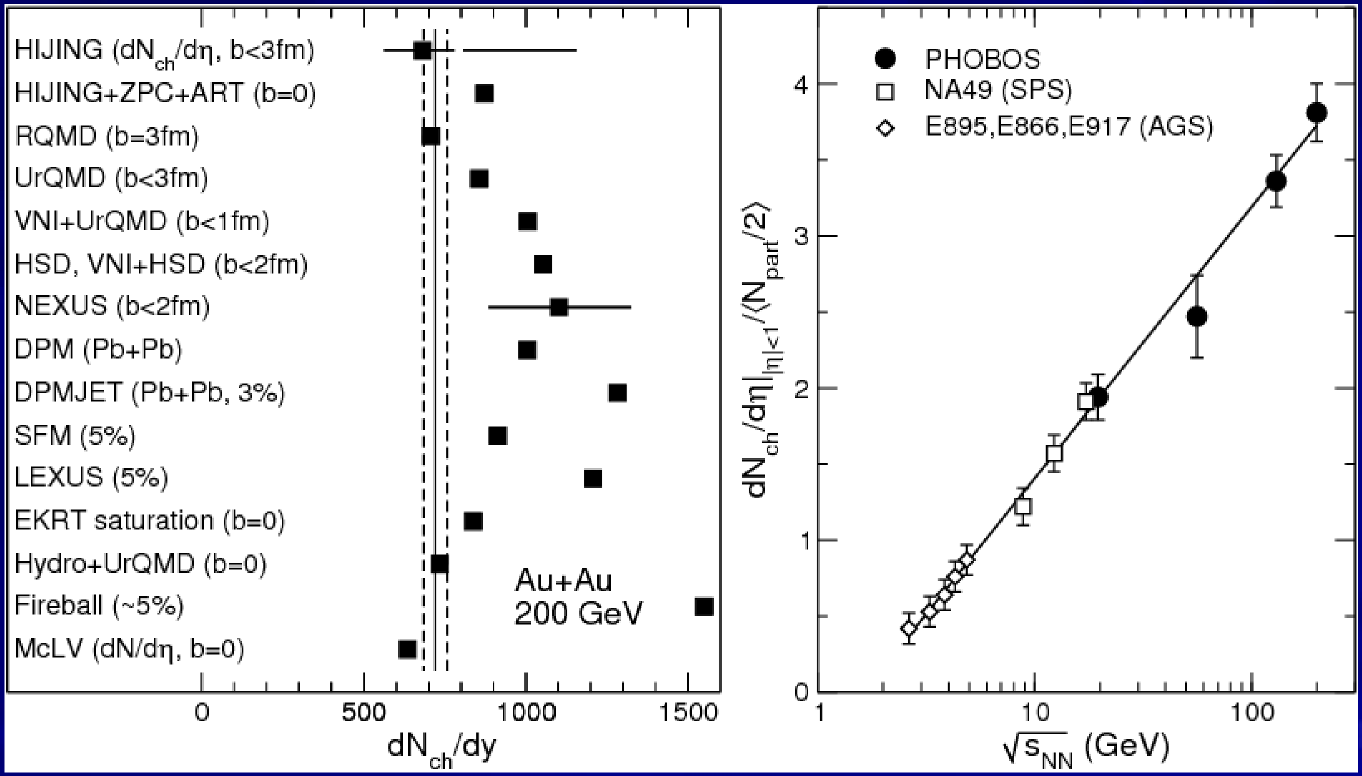
STAR

Charged multiplicity $dN_{ch}/d\eta$ at mid-rapidity (η~0) vs models

Model predictions at $\sqrt{s_{NN}}$=200GeV **$dN/d\eta$ $\sqrt{s_{NN}}$**

Lund strings →

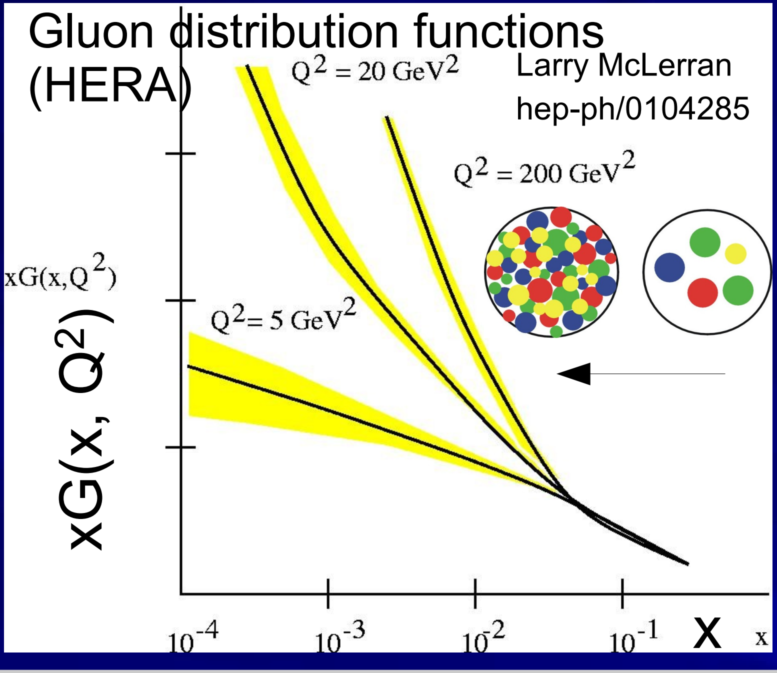
Gluon saturation (final state!) →

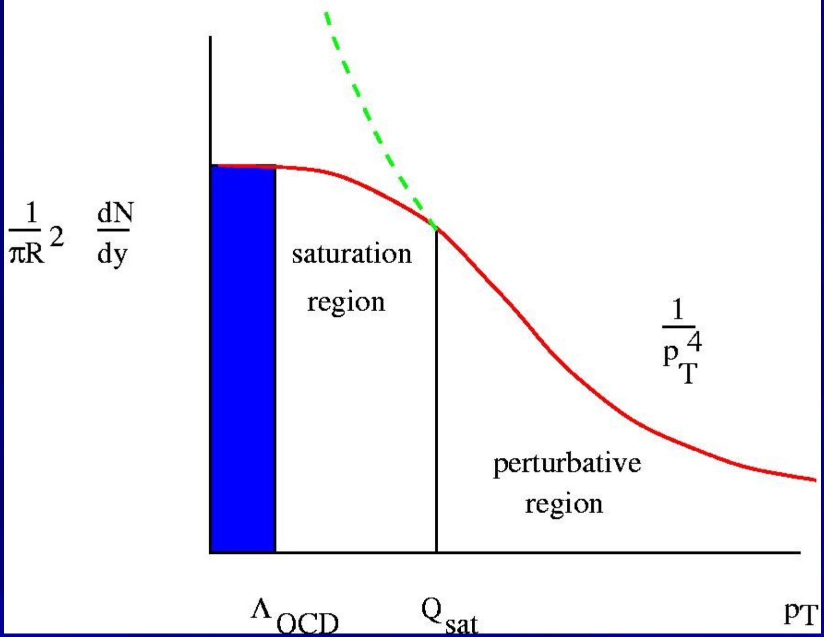


- From the $dN/d\eta$ and transverse energy one can estimate the energy density and one finds:

  ε~5GeV/fm^3 >> 1 GeV/fm^3 (numerical QCD critical ε)

Gluon saturation at small x



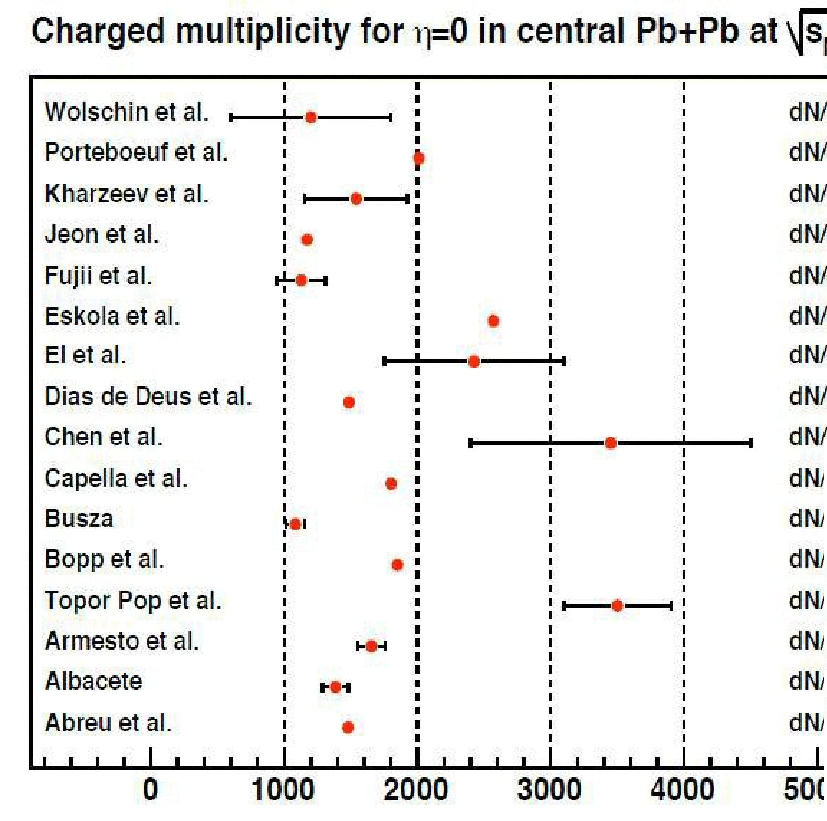


- **With increasing energy/momentum resolution the number of (small-x) partons in a hadron/nucleus grows rapidly (dominate soft physics)**
- **At the saturation scale Q_s partons begin to overlap in the transverse area of the nucleus (~$A^{1/3}$), which prevents further growth of the parton density**
- **Color-Glass-Condensate: The many partons can be treated as semi-classical fields and the initial condition at RHIC can be calculated**

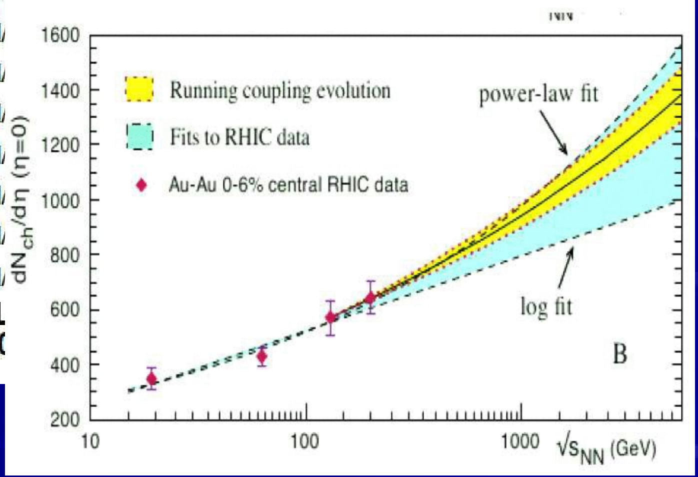
LHC predictions
Saturation is now largest

Gluon saturation (final state!) →

RHIC soft scaling →

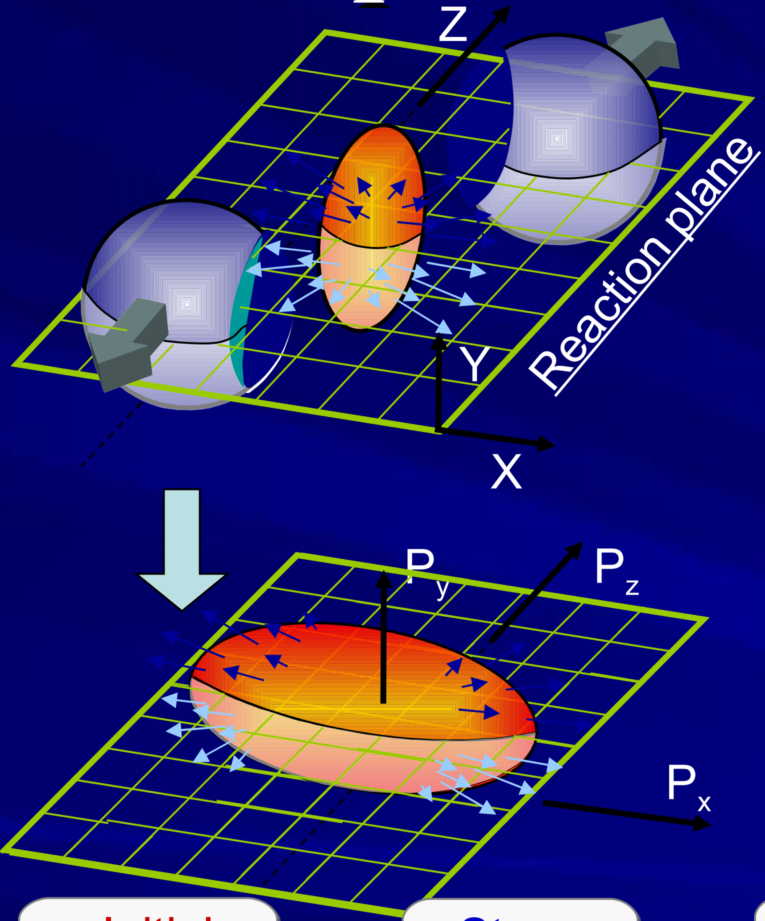


Compilation based on:
N Armesto et al 2008 J. Phys. G: Nucl. Part. Phys. 35 054001
Taken from pbm.



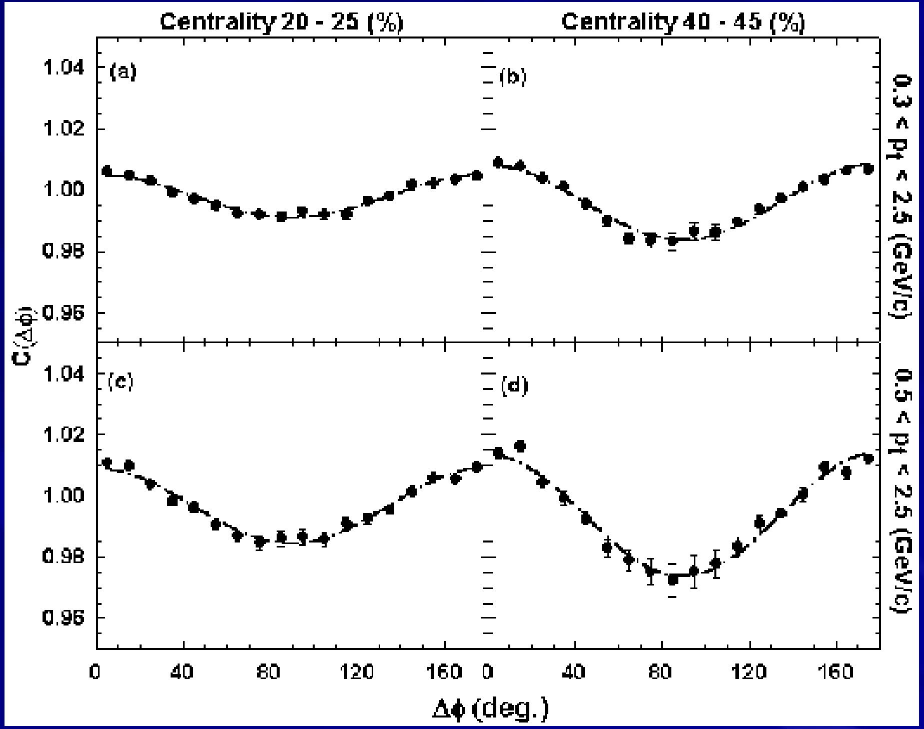
- Pre-RHIC: $dN_{charged}/dy$ (LHC) = 8000!
- Day 1 physics will determine the role of the hard scale at LHC (very high energies)

Elliptic flow (v2) unique to heavy ion collisions



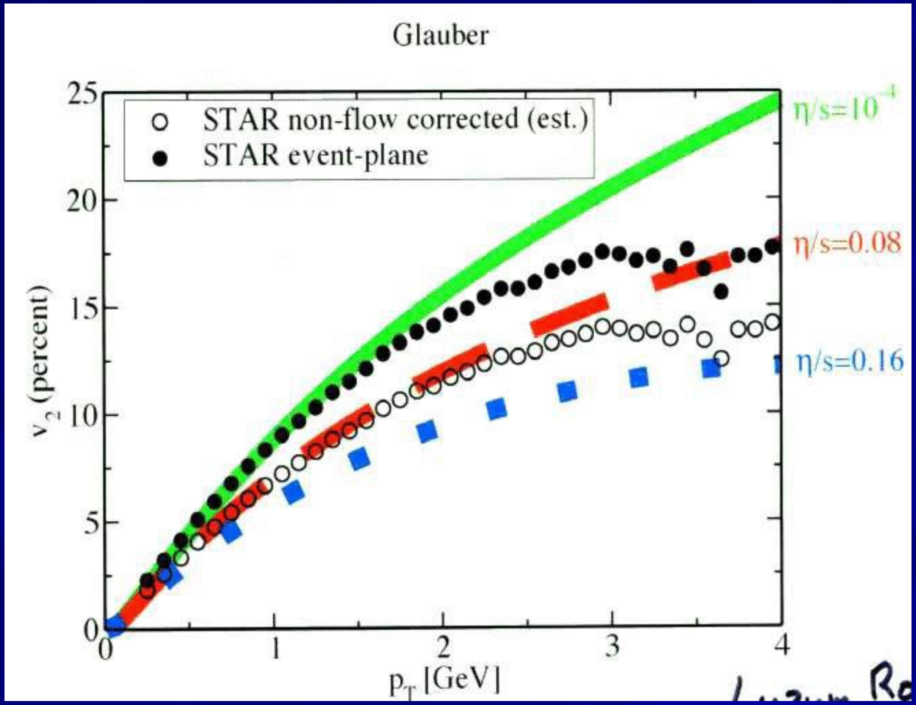
Fourier decomposition:

$dN/d\phi = 1 + 2\,V_2\cos(2\,\Delta\phi)$



Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

Elliptic flow is close to ideal (non-viscous) hydrodynamics



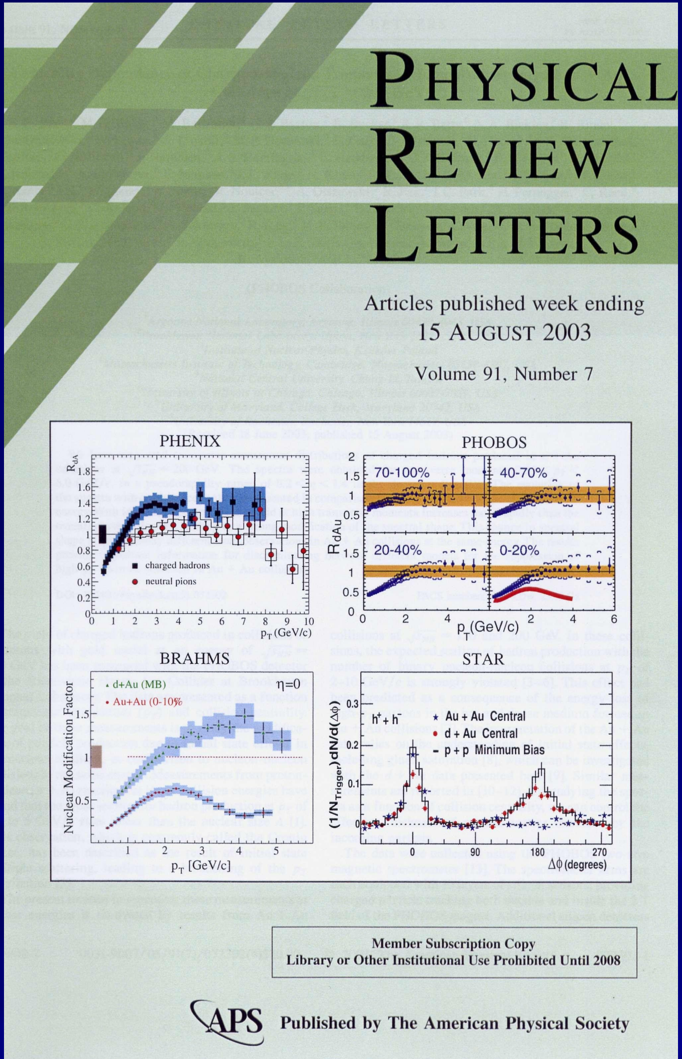
Calculation by
M. Luzum and
P. Romatschke

- The big surprise at RHIC was the agreement with hydro calculations and the large flow out to high pT (what is flowing there? Ask me:-)
- This leaves little room for dramatic increases at LHC (by conventional hydro) < 25% increase.

AdS/CFT: The fluid is perfect!

- Anti-de-Sitter/Conformal Field Theories is a math trick
- Weakly coupled 5d super gravity is dual to QCD like theory
  - Strongly coupled
  - Conformal = no intrinsic scale = deconfinement = QGP
  - Infinite number of colors
  - No running coupling
- Some big results from AdS/CFT
  - Strongly coupled theories can have gas like energy densities
  - Universal (for all forms of matter) lower bound on the viscosity to entropy density ratio: $\eta/s \geq 1/(4\pi)$
- However, also some results disagree with experiment
  - J/Ψ suppression as a function of p_T
- Hope is to find dual QCD theory

Hard probes (pQCD): parton-parton interactions



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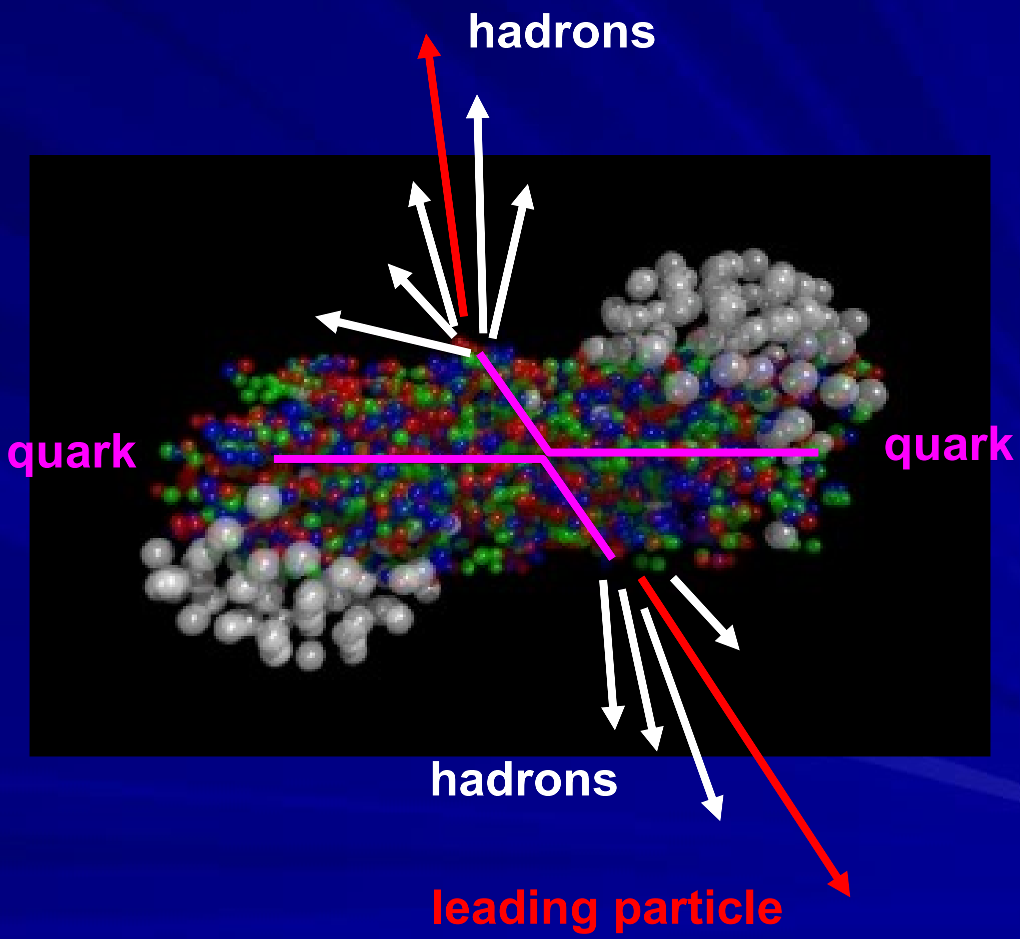
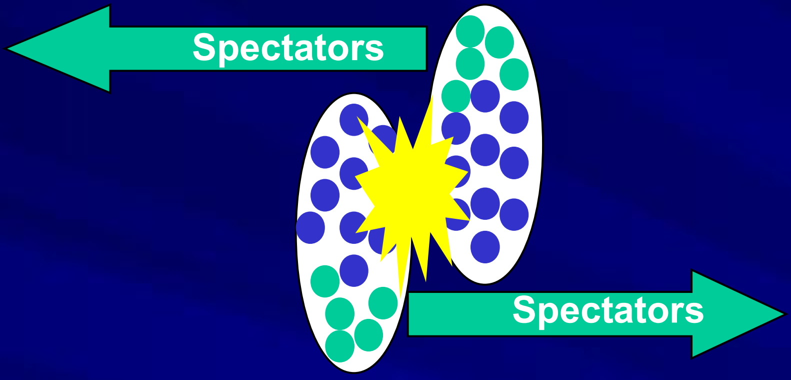
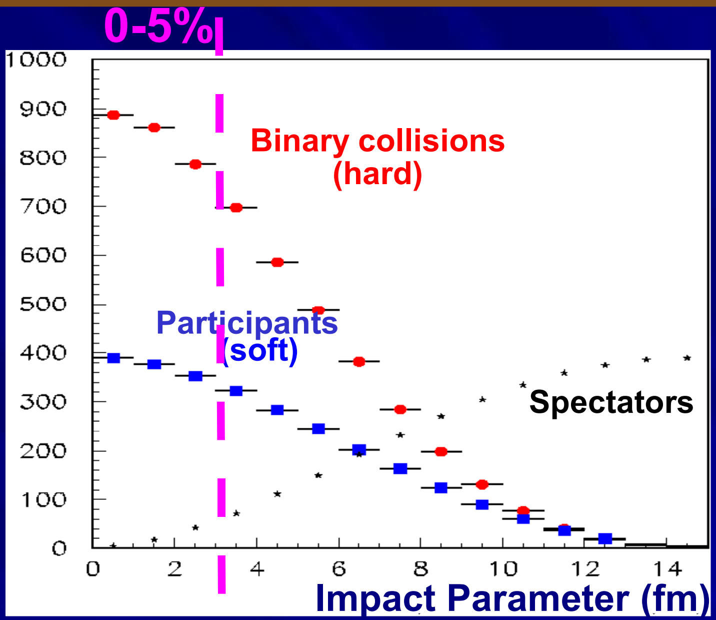


Heavy Ion Jargon

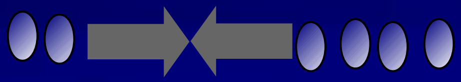
- **Centrality (ex. for Au+Au):**





Participants = 2*197 - Spectators

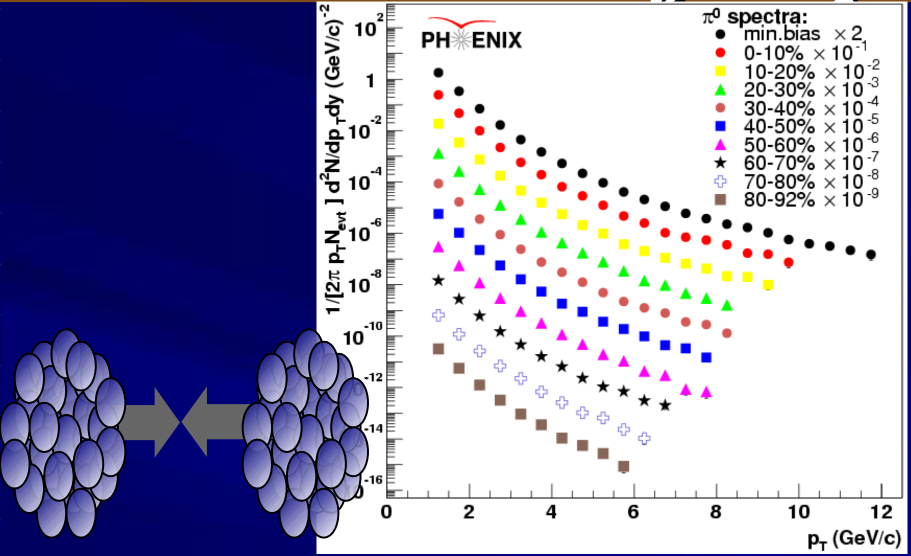
- **The total energy is proportional to the participant**
- **The number of parton-parton (quark-quark, quark-gluon, gluon-gluon) is proportional to the binary collisions**
- **Example:**



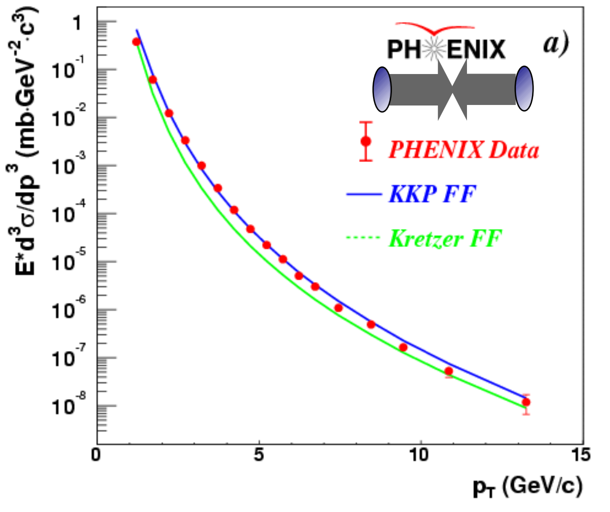
6 participant
8 binary collisions
(pp has 2 participant and 1 binary collision)

The nuclear modification factor for pions (1/2)

$$R_{AA} = \frac{d^2N^{AA}/dp_T\,dy}{\langle N_{bin}\rangle\, d^2N^{NN}/dp_T\,dy}$$



Nbin



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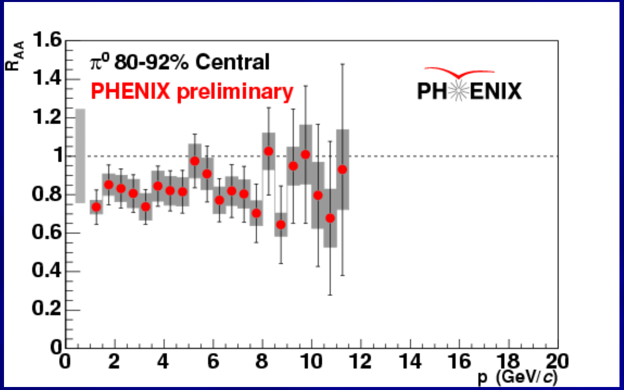
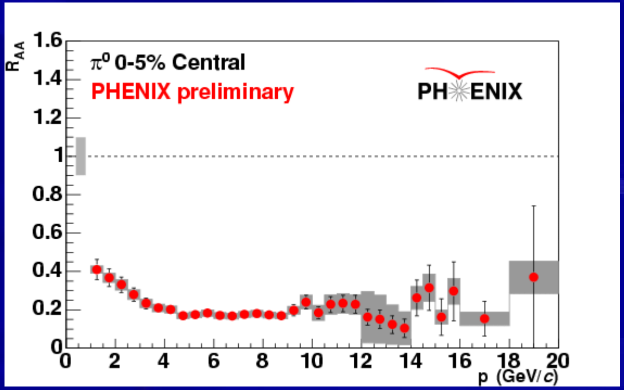
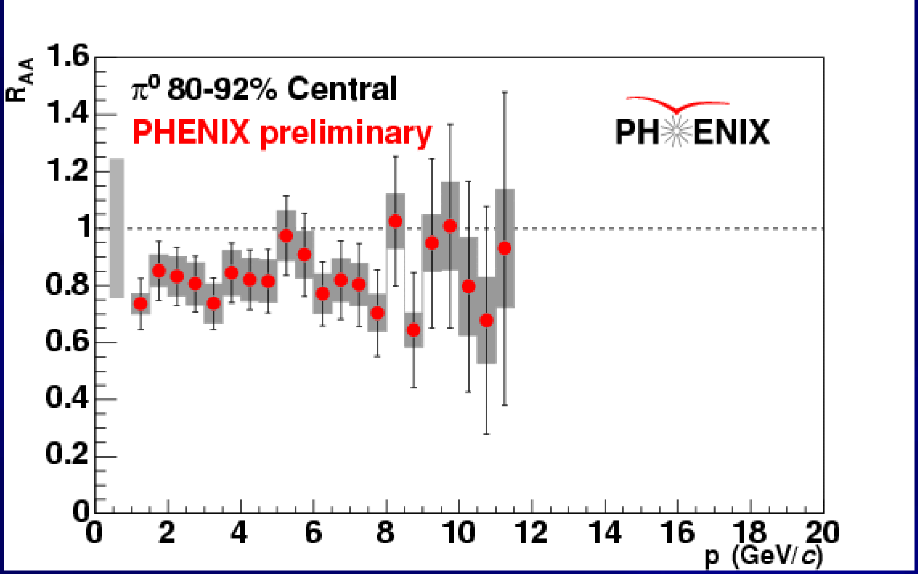
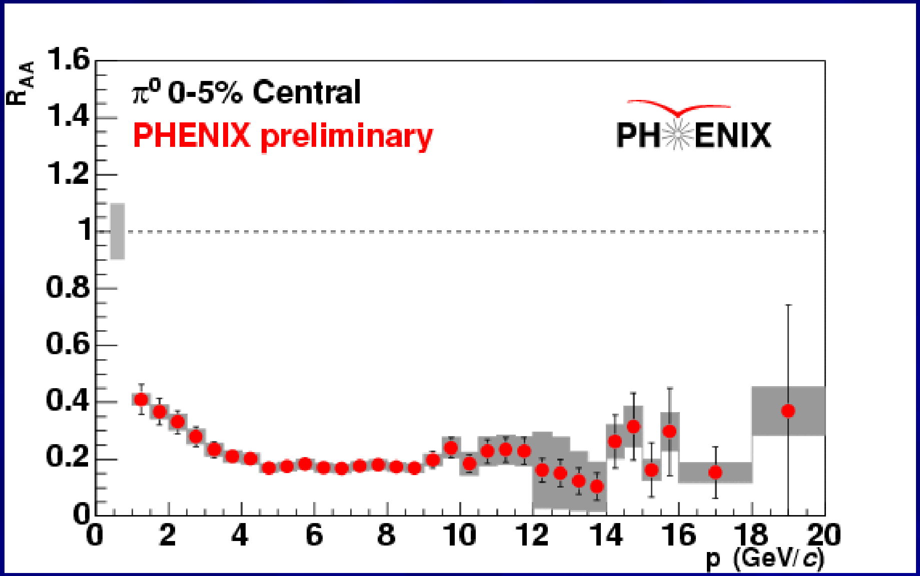




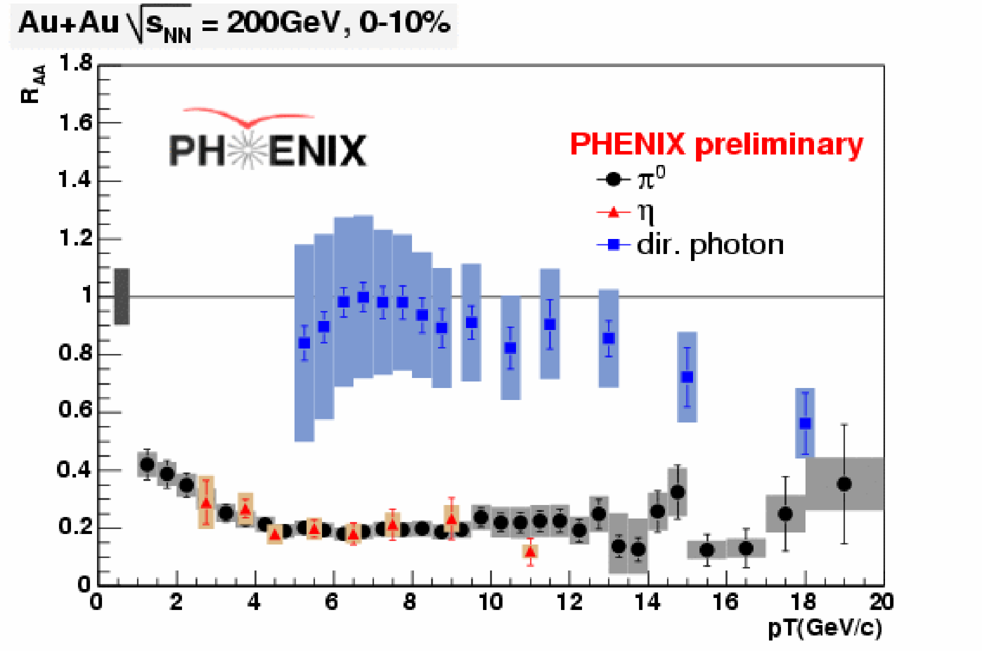
The nuclear modification factor for pions (2/2)



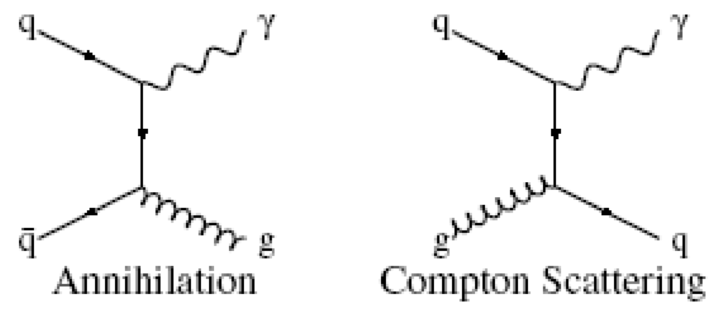


- In central collisions we observe only 20% of the remnants from parton-parton collisions that we expected to observe!
- What happens to the rest?
  - They loose energy as they go through the high energy matter!
  - This is the QCD signature we looked for!
- But first let us consider other alternatives!

Could the binary scaling be wrong?

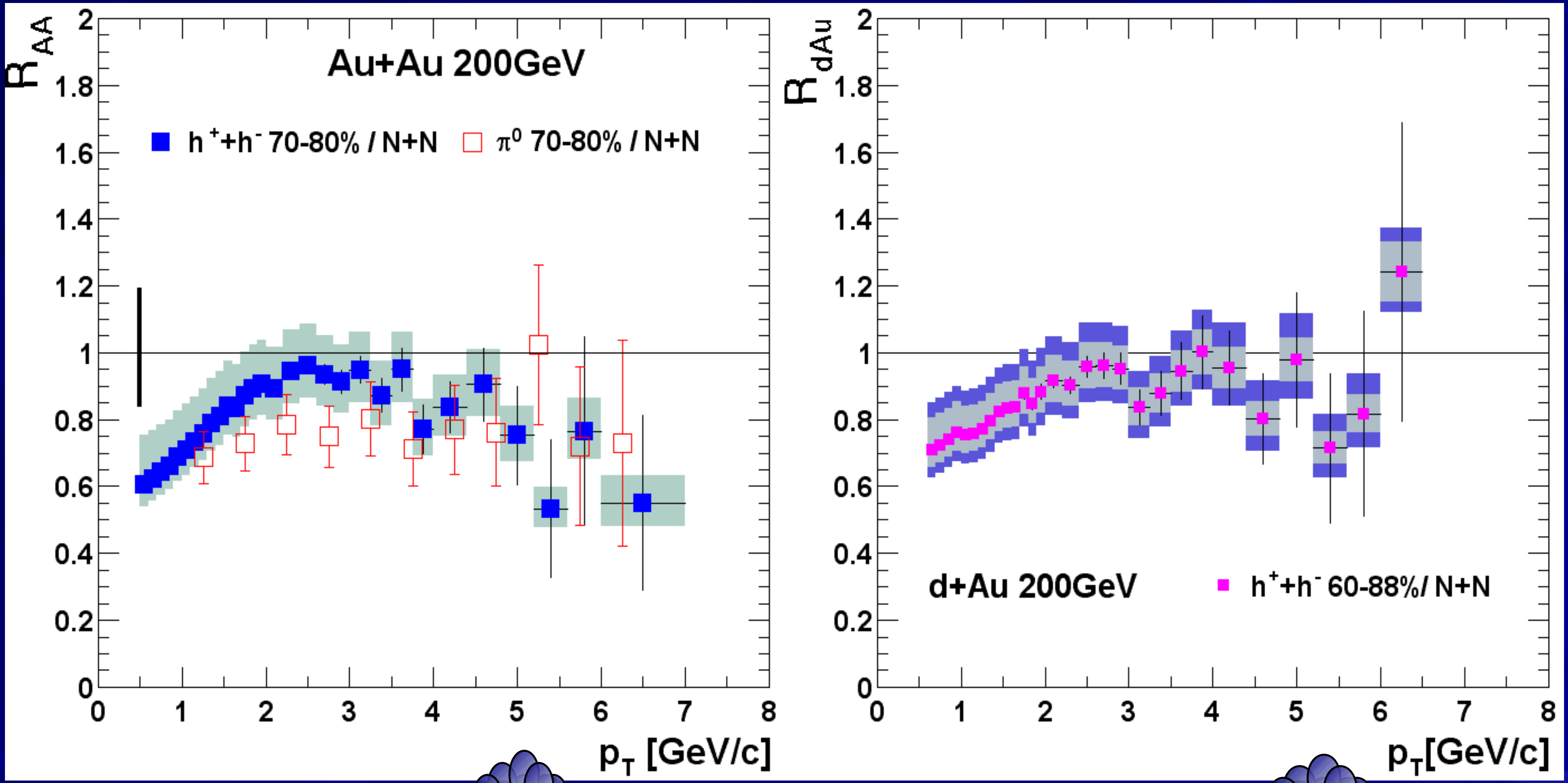


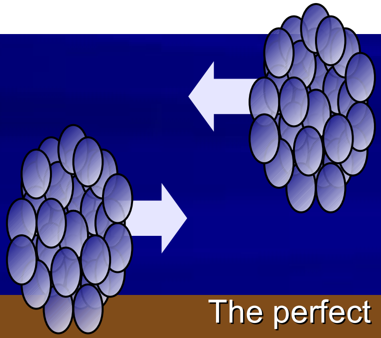
Source of direct photons

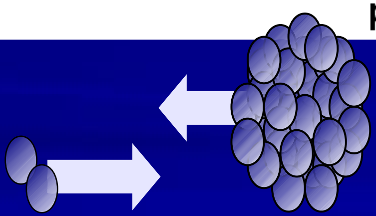


- Direct photons does not interact with final state hadronic matter!
- Direct photons shows no nuclear modification confirming binary scaling of hard processes!

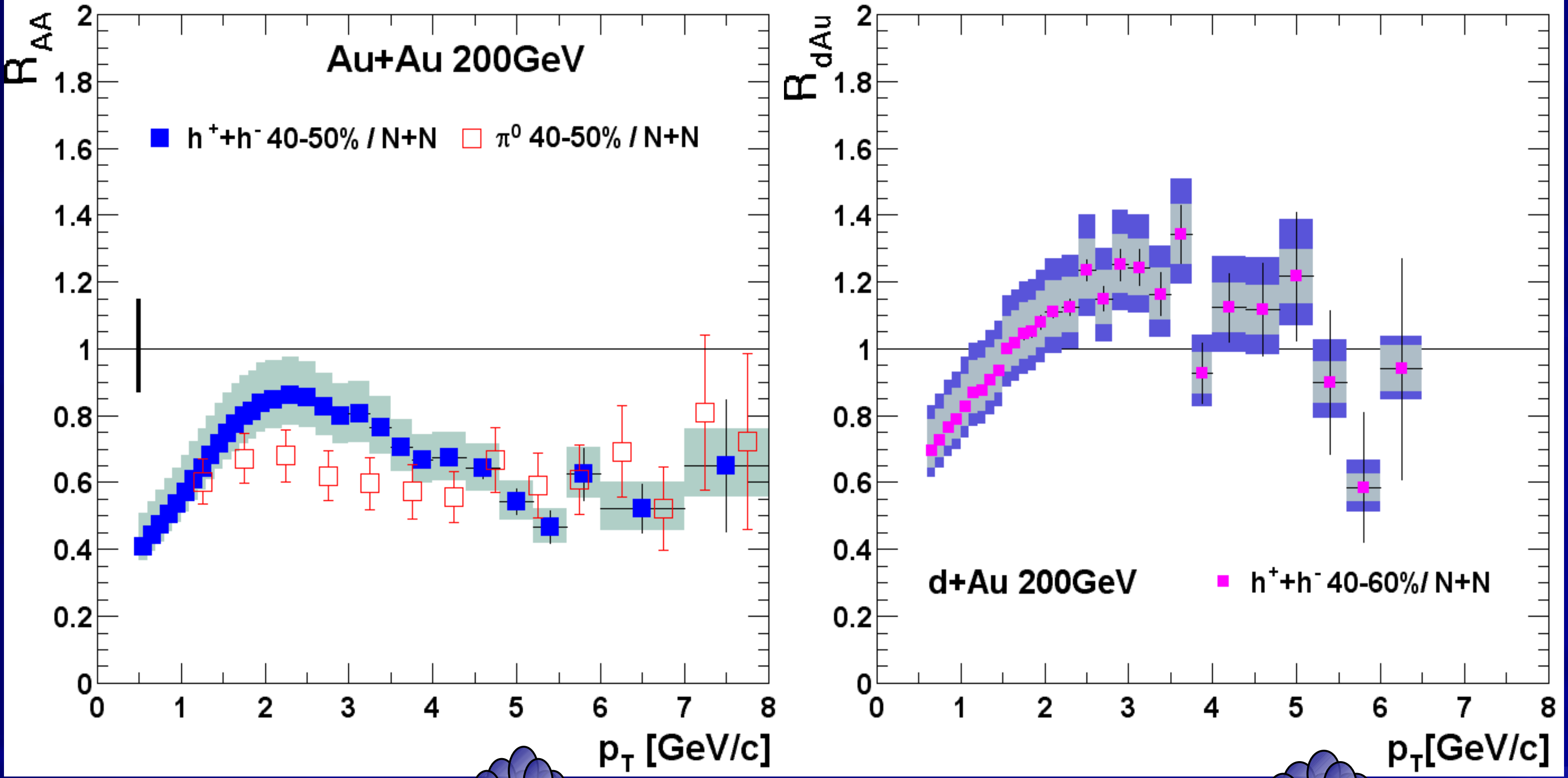
Could it be an initial state effects? Au+Au vs d+Au

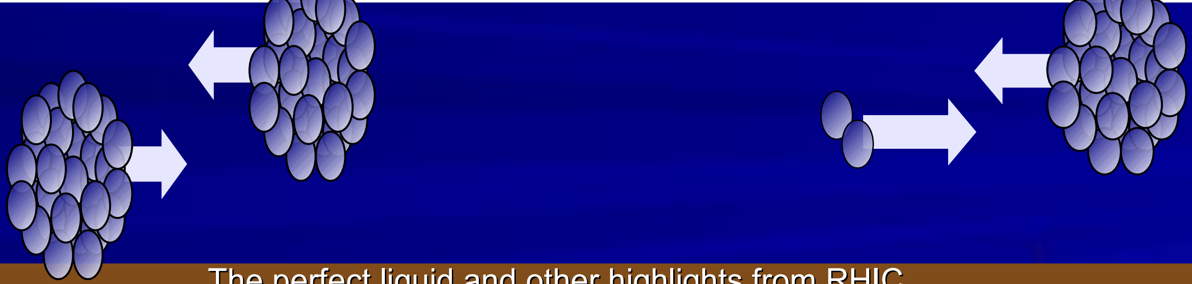




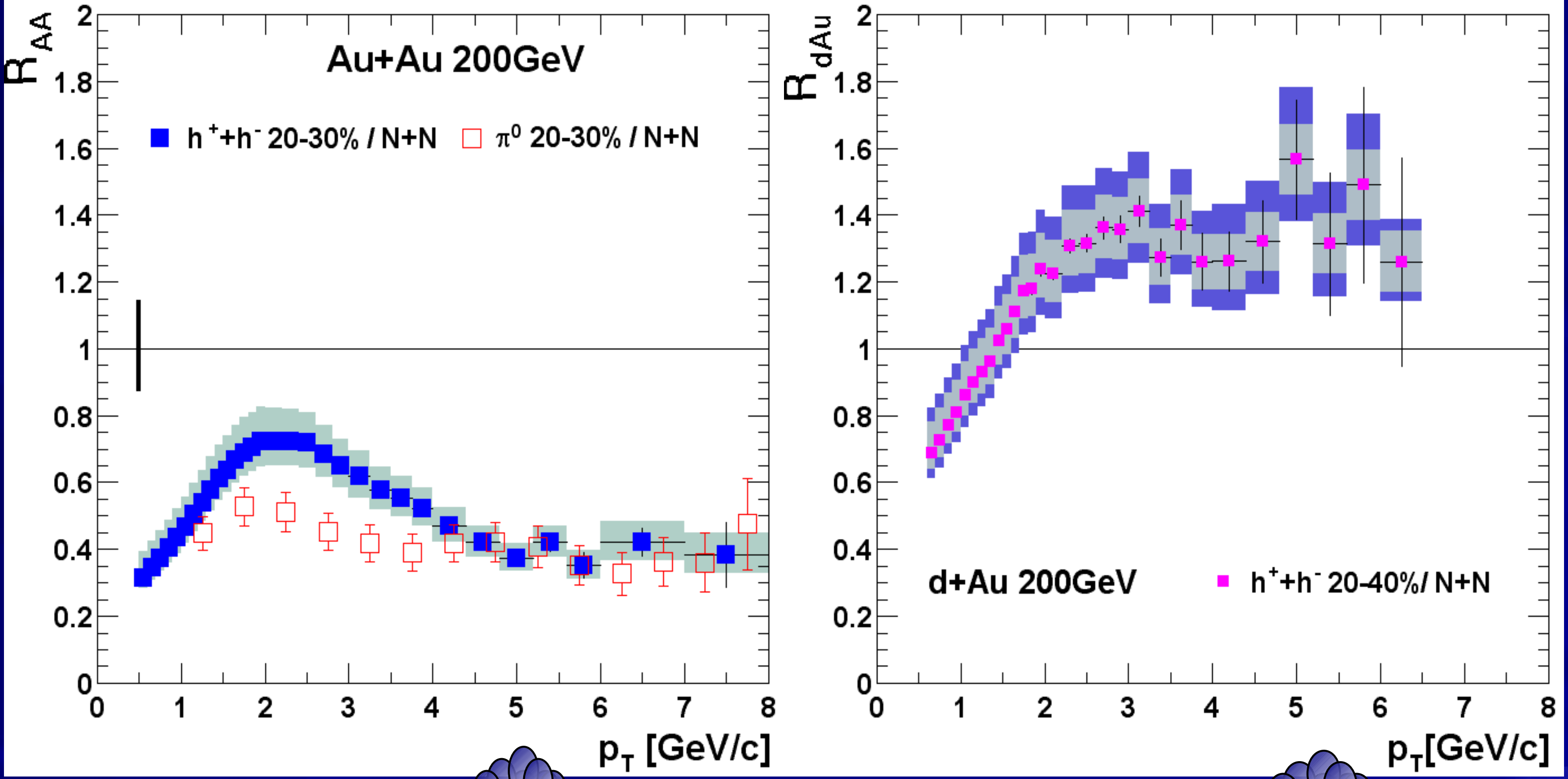


Could it be an initial state effects? Au+Au vs d+Au

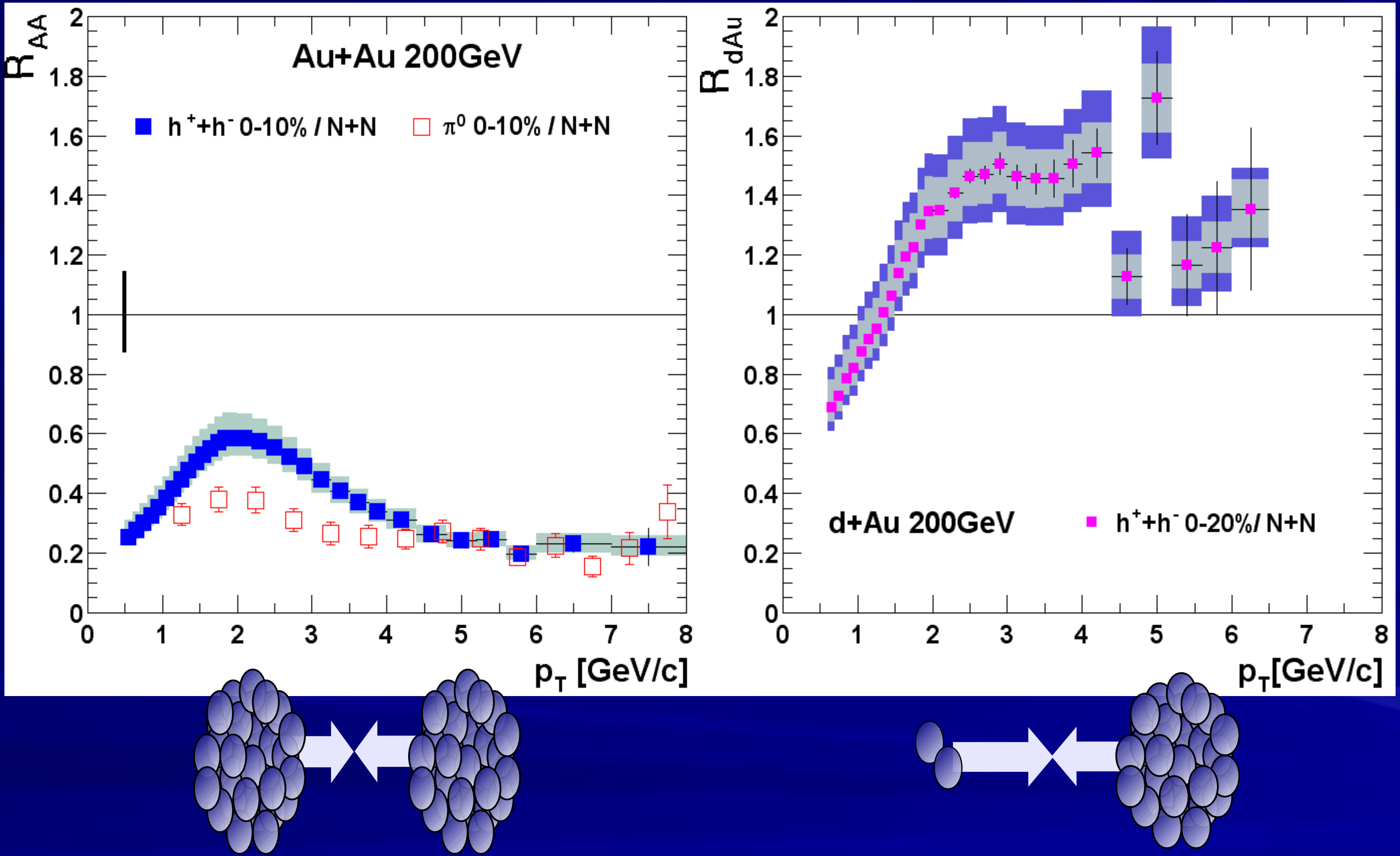




Could it be an initial state effects? Au+Au vs d+Au

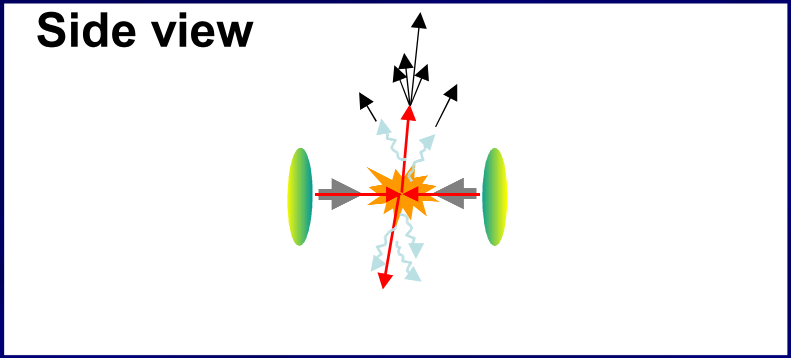


Could it be an initial state effects? Au+Au vs d+Au

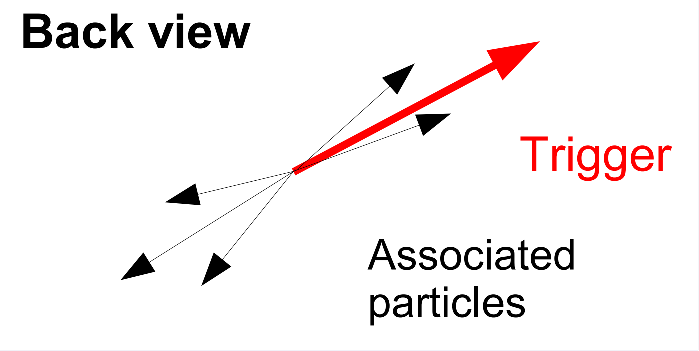


So it must be a final state effect!

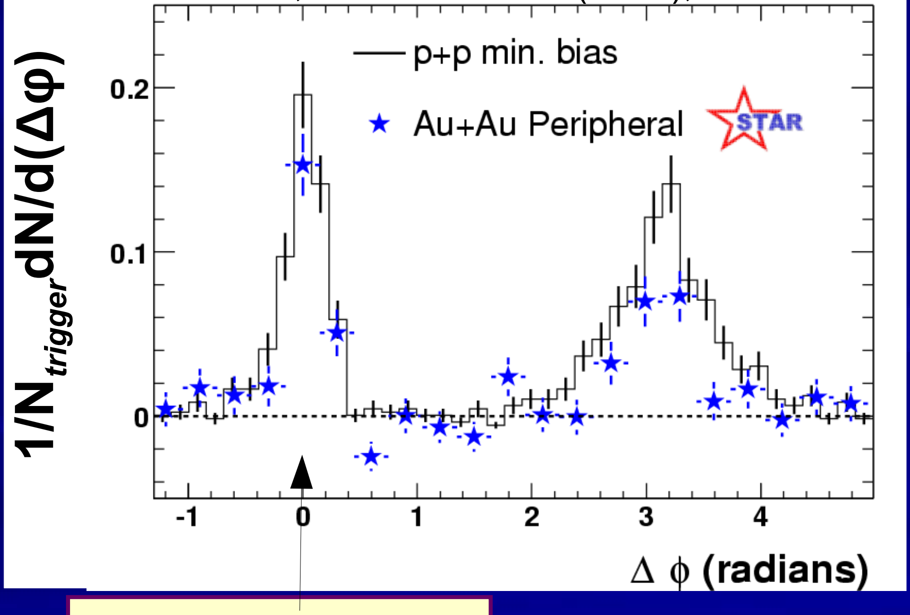
The suppression is due to energy loss in the medium



Most jets are created back to back!



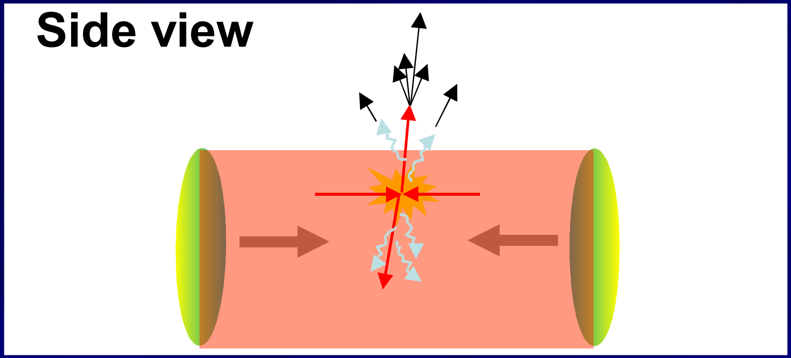
Adler *et al.*, PRL90:082302 (2003), STAR



4 < p_T(trig) < 6 GeV/c

p_T(assoc) > 2 GeV/c

The suppression is due to energy loss in the medium



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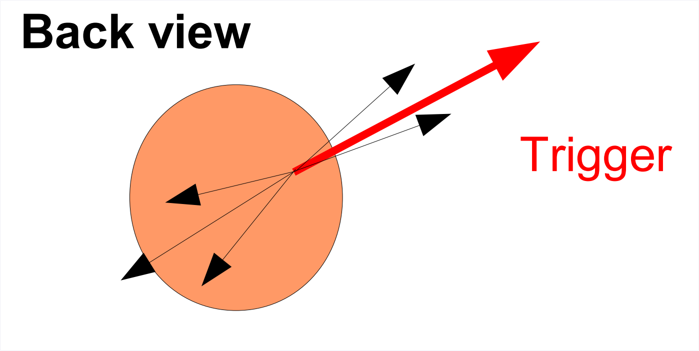

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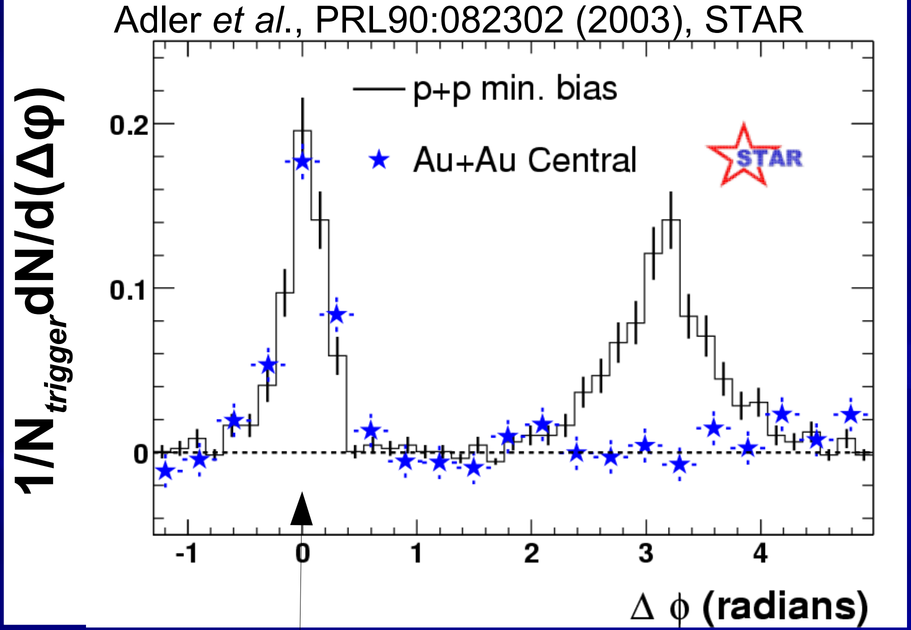
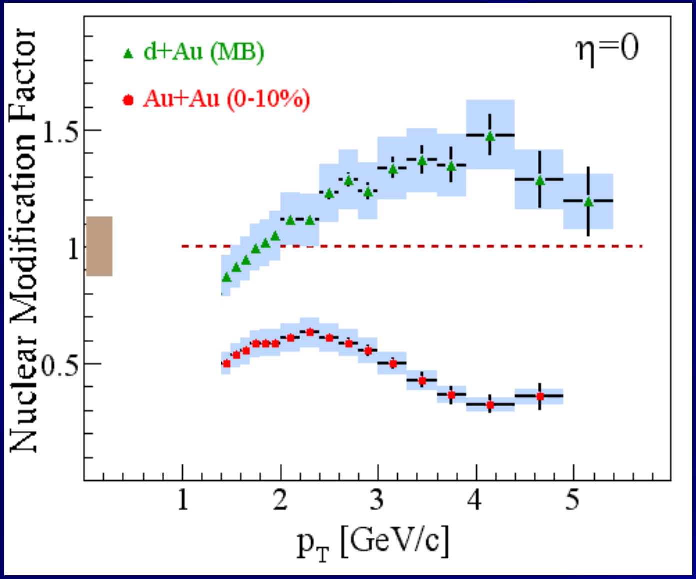


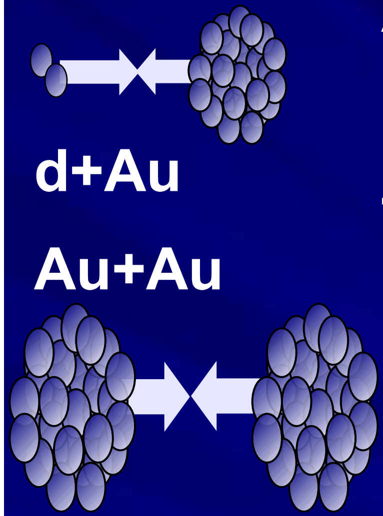
$4 < p_T(\mathrm{trig}) < 6$ GeV/c

$p_T(\mathrm{assoc}) > 2$ GeV/c

A large energy loss requires a QCD interacting medium, i.e., a colored medium!

Au+Au vs d+Au
Hot vs cold nuclear matter

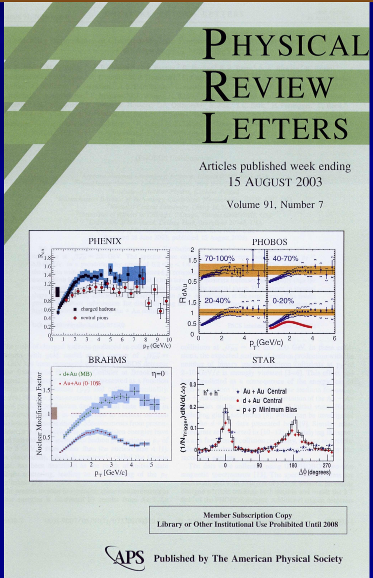




d+Au

Au+Au

All 4 experiments published together in PRL:



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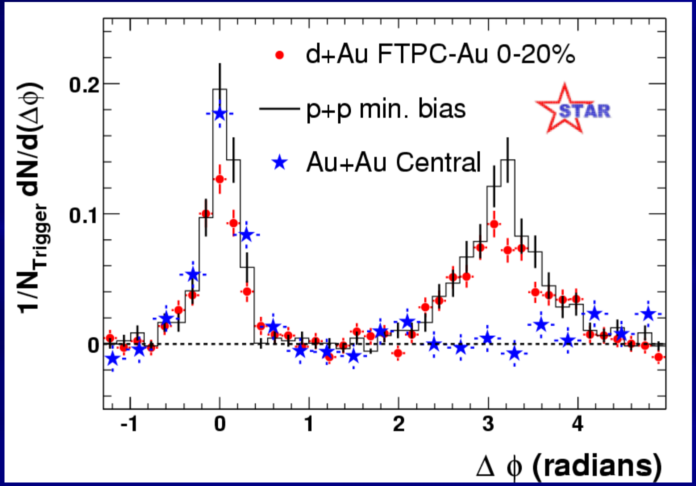
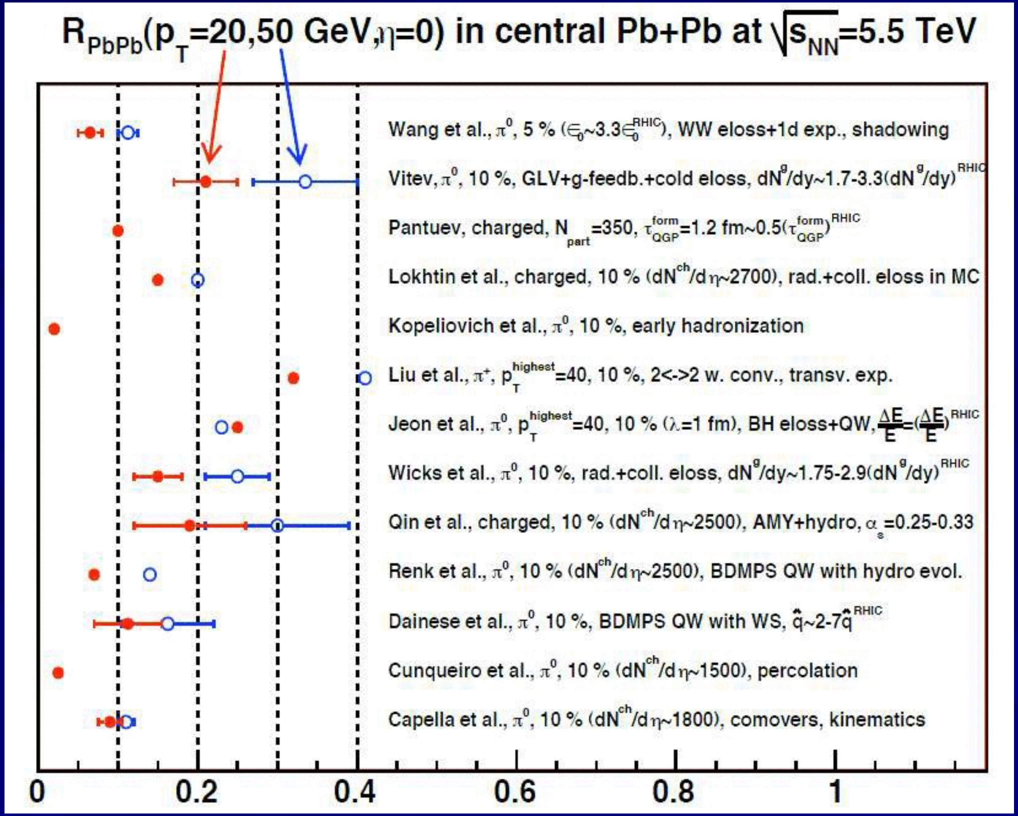


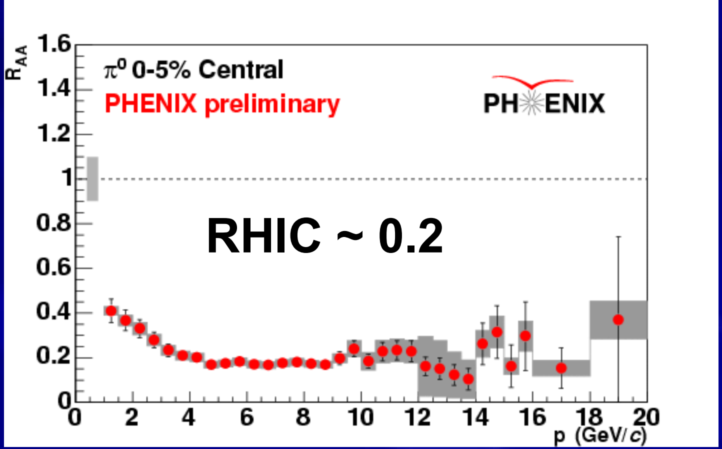
No suppression seen in d+Au
→ Quarks and gluons loose/radiate energy as they interact with the colored quarks and gluons of the created matter.
This suggests that the quark gluon plasma has been discovered!

Predictions for LHC



$R_{PbPb}(p_T=20,50\ \mathrm{GeV}, \eta=0)$ in central Pb+Pb at $\sqrt{s_{NN}}=5.5$ TeV

Compilation
based on:
N Armesto et al 2008
J. Phys. G:
Nucl. Part. Phys.
35 054001
Taken from pbm.



RHIC ~ 0.2

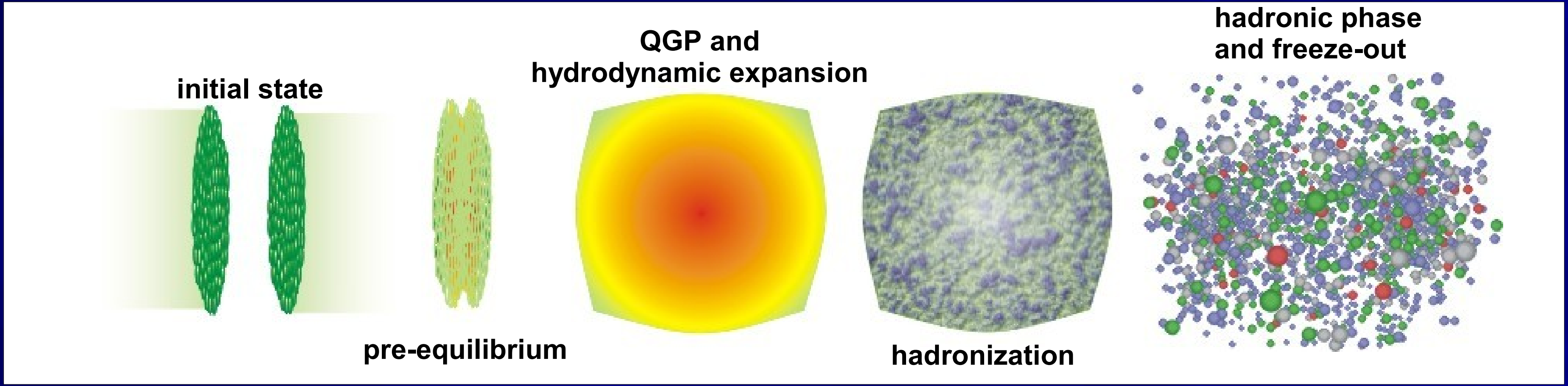
- Given that the experimental uncertainty probably will be ~0.1 the models are not that different (no punch through)
- Difficult to get much larger suppression without initial state effects due to the large unsuppressed surface

Summary:

- Multiplicity dN/deta (dEt/dy, particle ratios, pT slopes) have established that we are above Tc
- Elliptic flow indicates that the medium interacts early – thermalized and collective (strongly interacting → sQGP)
- Jet quenching (light quarks) shows that jets interacts strongly with the medium → medium is colored
- Theoretical models fails to describe more than one effect at a time
- Day 1 measurements will complete the energy systematics of the bulk observables and jet quenching (and hopefully provide new unexpected results) in a regime where pQCD should work even better

Heavy ion collisions: The study of high energy QCD

The evolution of a heavy ion collision

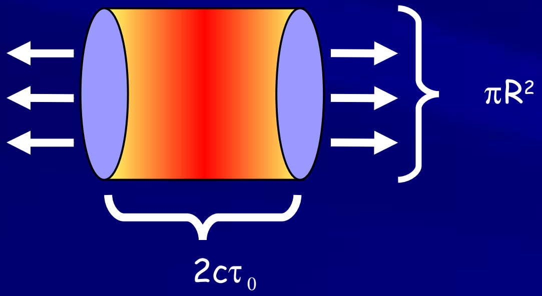


- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally only the final state particles are observed, so the conclusions have to be inferred via models

"Measured" initial energy density

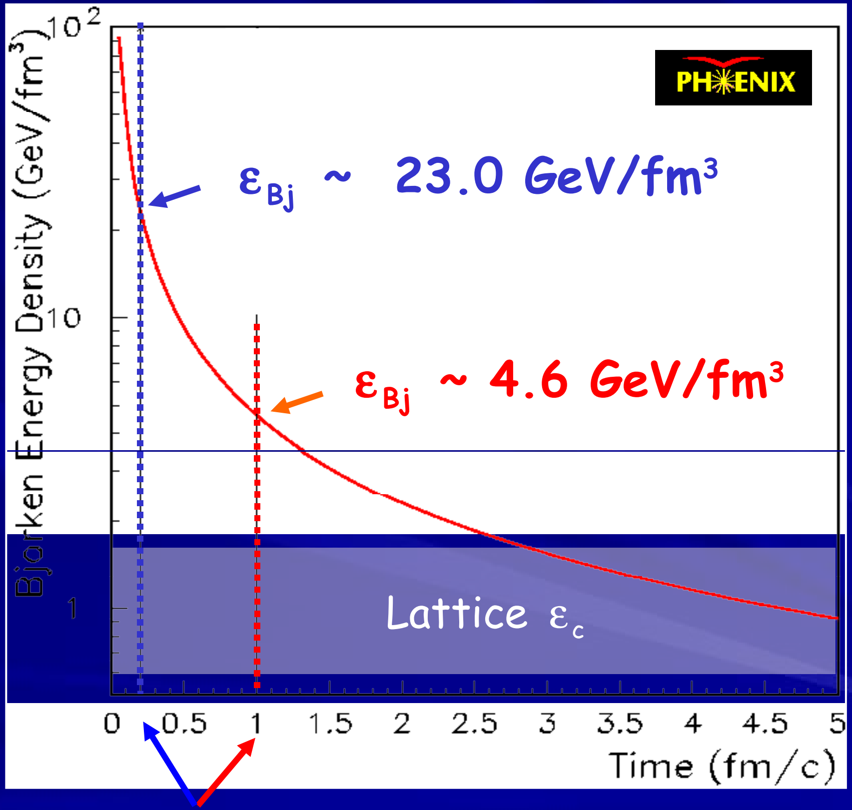
Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy E_T

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)$$



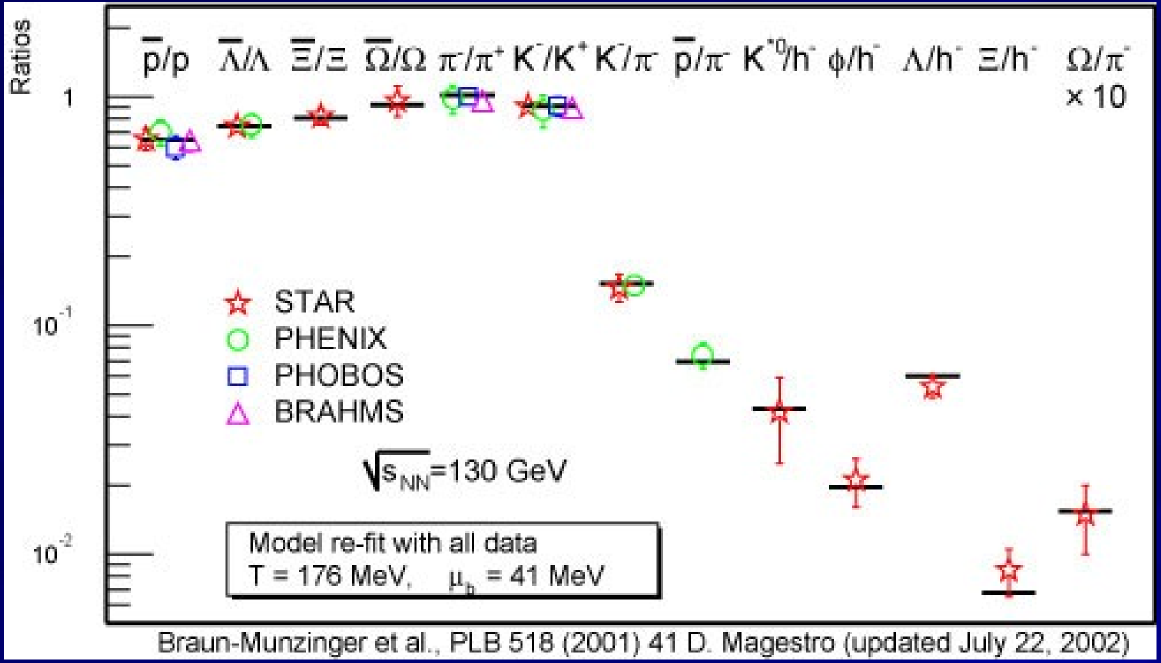
PHENIX: Central Au Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\, GeV$$

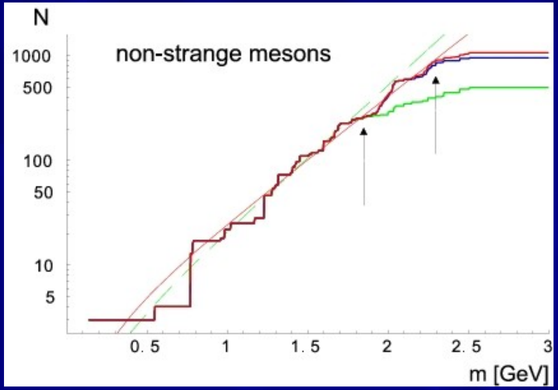


Formation(thermalization) time ?

Identified particle ratios: T and μ_B at freezeout



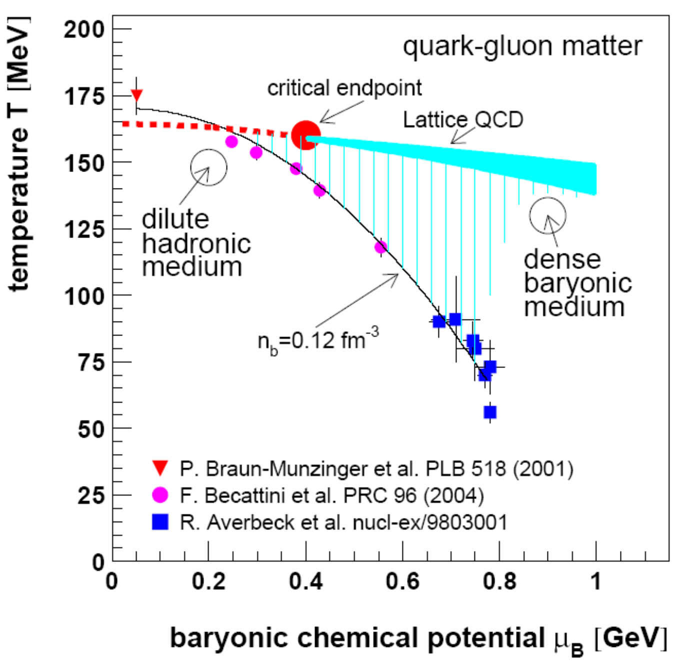
Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

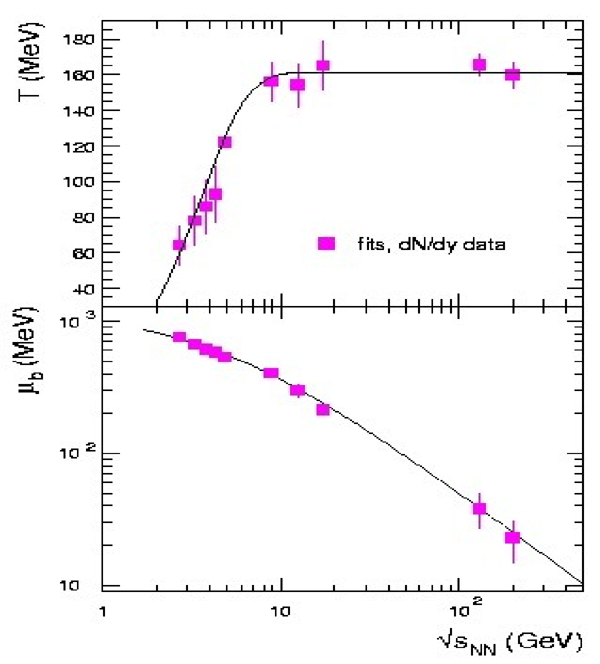


1. Generate hadrons with weights: exp(-(m+μ_B)/T)
2. Decay strongly
3. Compare to data

- Particle ratios are well described by statistical models when decay from hadronic resonances are taken into account (only QCD input are the masses and decays)
- The temperature is consistent with what we expect from Lattice QCD calculations for the transition temperature

The QCD phase diagram with the measured T and μ_B





T_{lim} = 161 ± 4 MeV

A. Andronic,
P. Braun-Munzinger,
J. Stachel,
nucl-th/0511071

Because of the simple beam-energy systematics statistical models have predictive power!

- The statistical description of particle rations is also good for lower energies: AGS and SPS. The temperature saturates at T~160 MeV indicating that the system has crossed the phase boundary (→ LHC prediction~RHIC)
- But p+p ratios can be described with a similar (canonical) formalism and T! So it is a hadronization attribute.

Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

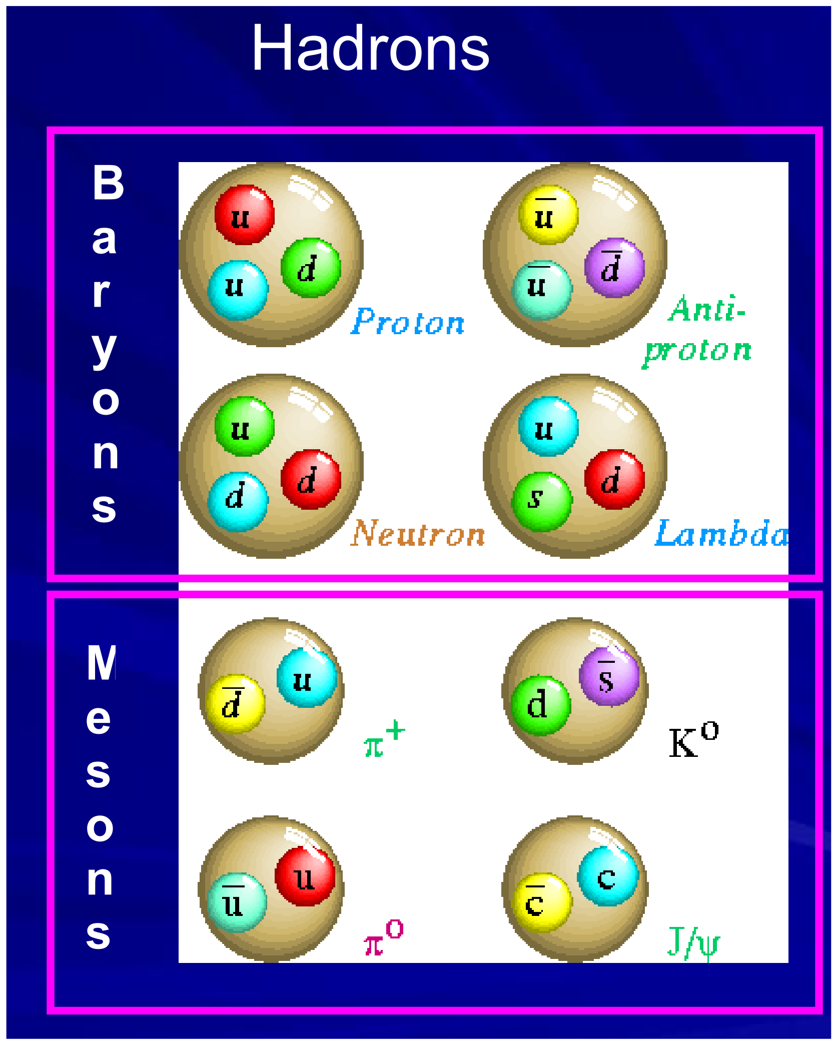
Hadrons have to be colorless

Baryons have all 3 colors

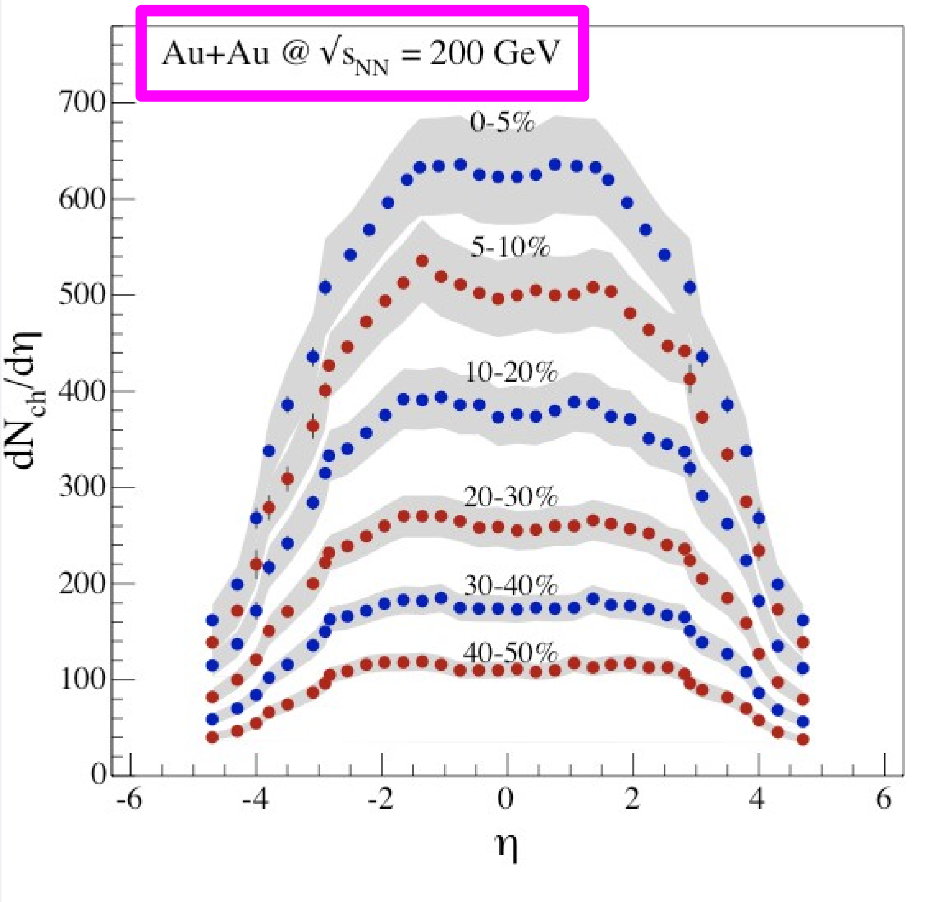
Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!

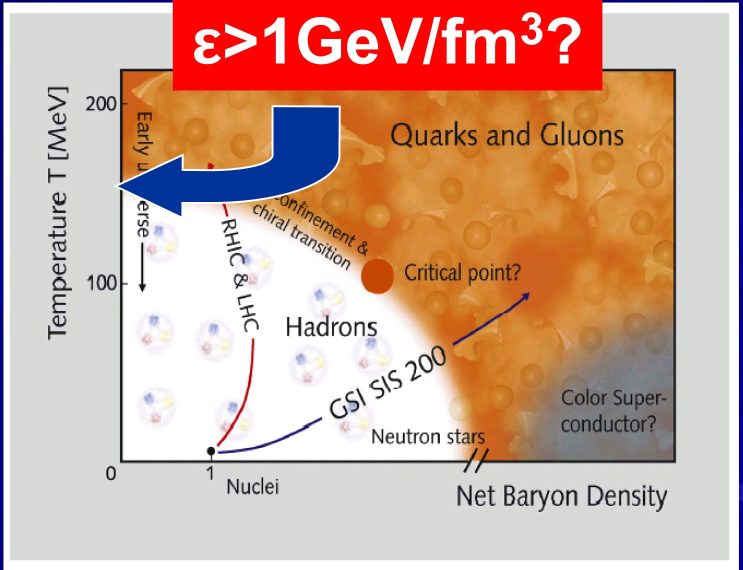


Charged Particle Multiplicity $dN/d\eta$



According to Bjorken:

$$\epsilon \approx \frac{1}{A_t}\frac{dN}{d\eta}\frac{1}{\tau} < E_t >$$

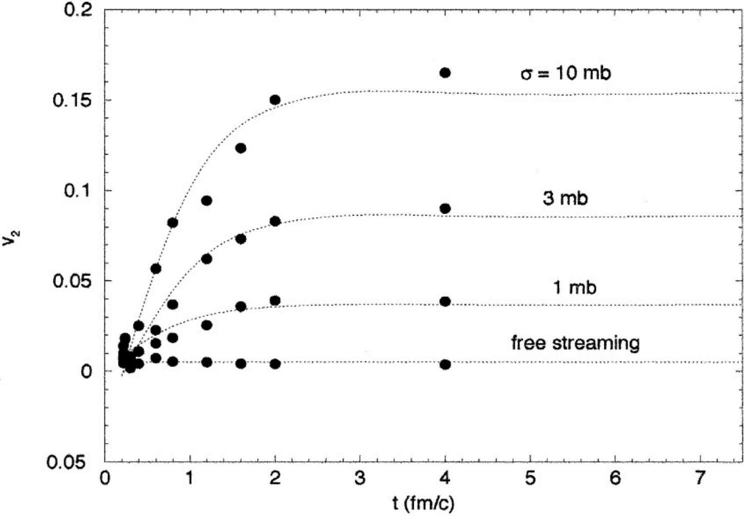

ε>1GeV/fm^3?

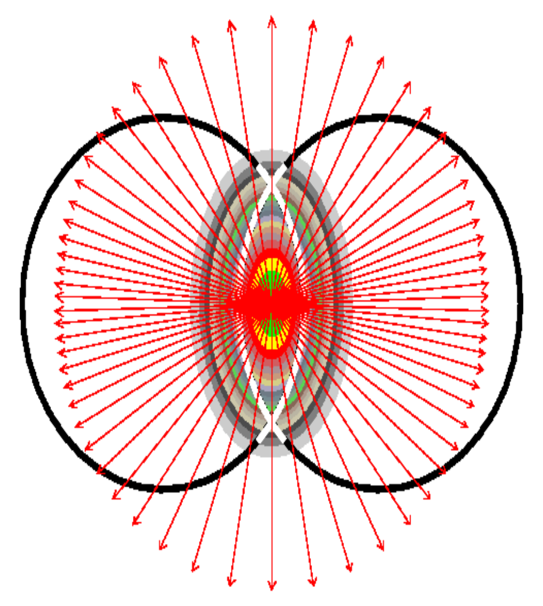
Estimate the energy density, assume <Et>~0.5GeV,

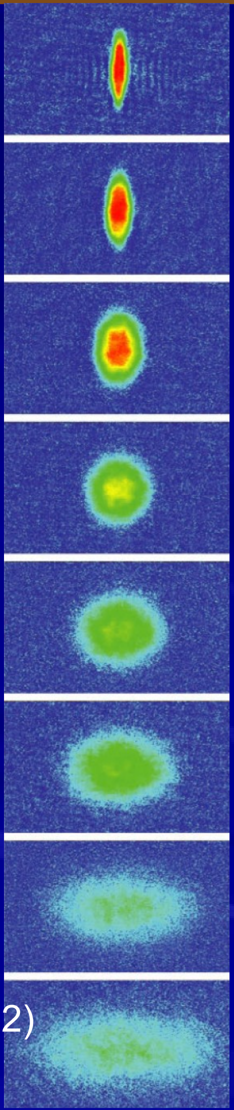
Answers

- Each nucleon-nucleon interaction produces on average a spherical symmetric distribution. Only by interacting elliptic flow is generated

ng, Gyulassy, Ko, Phys. Lett. B455 (1999)



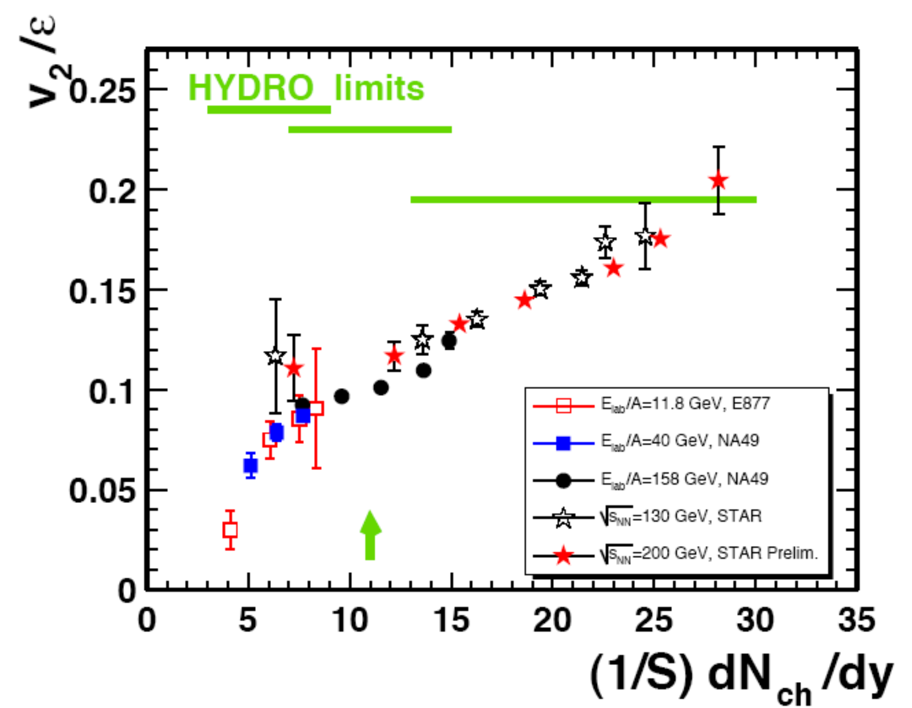




- Flow is strongest in the event plane because of the stronger matter gradient
  - hydrodynamic explanation

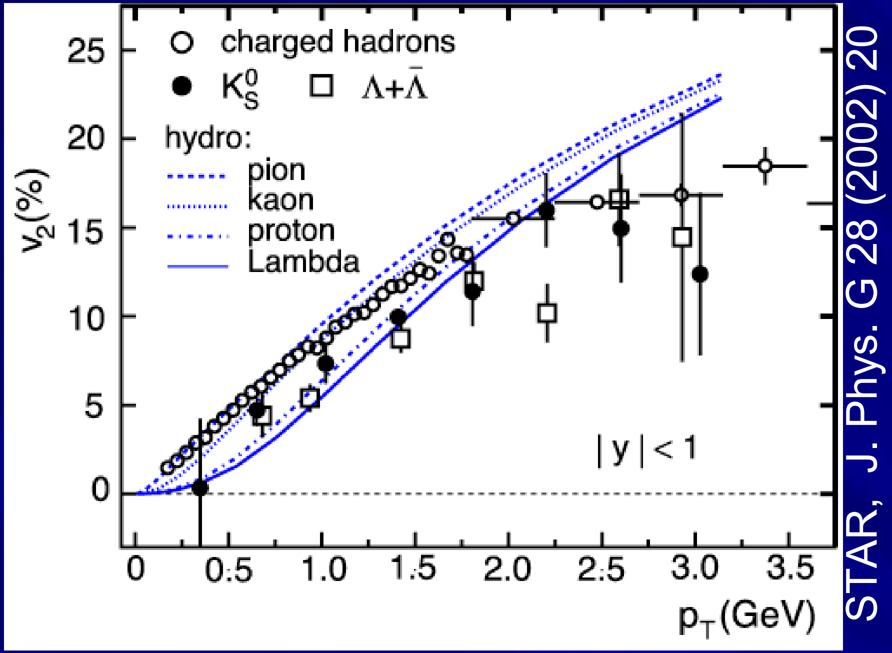
SCIENCE Vol: 298 2179 (2002)

Elliptic flow at RHIC is "Maximal"



- Relativistic hydrodynamic predicts elliptic flow
  - The high energy medium interacts very strongly immediately after being formed
  - Medium does not behave as a gas, but an almost perfect fluid!
- Question: Where is QCD dynamics?

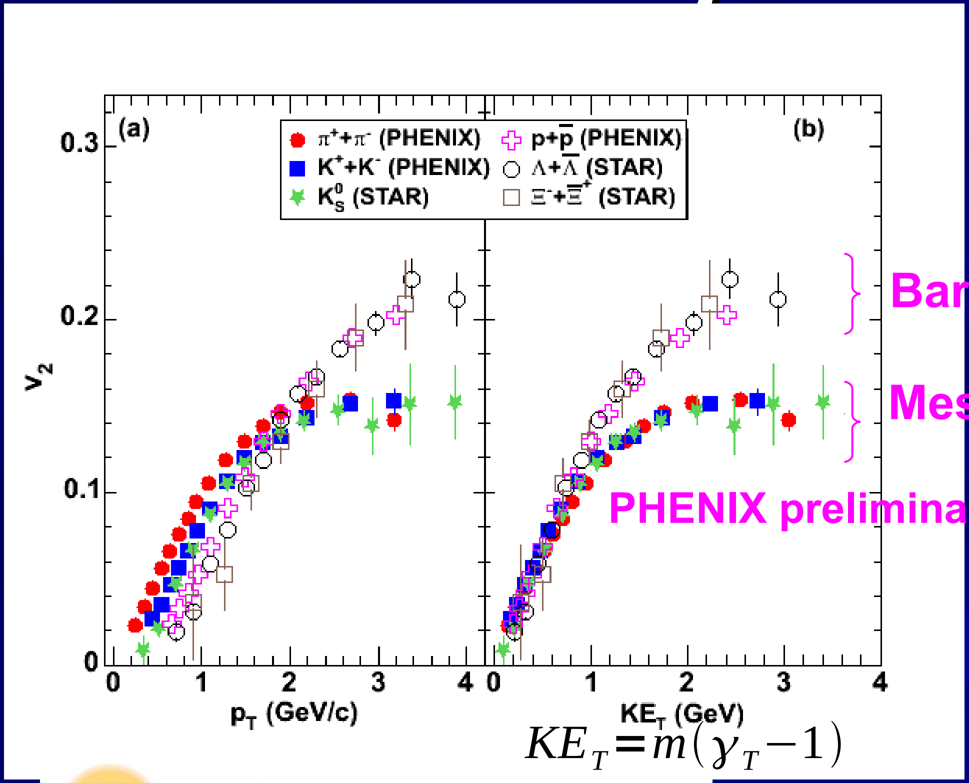
v2 at RHIC



STAR, J. Phys. G 28 (2002) 20

- Hydrodynamic predicts v2 (for p_T<2GeV/c)
  - Mass difference comes from velocity/flow at freezeout
  - v2 at AGS and SPS is below hydro limit
- Strong interactions are really strong => use hydro
- Where is QCD dynamics?

What is flowing at high pT: The quarks are flowing!?

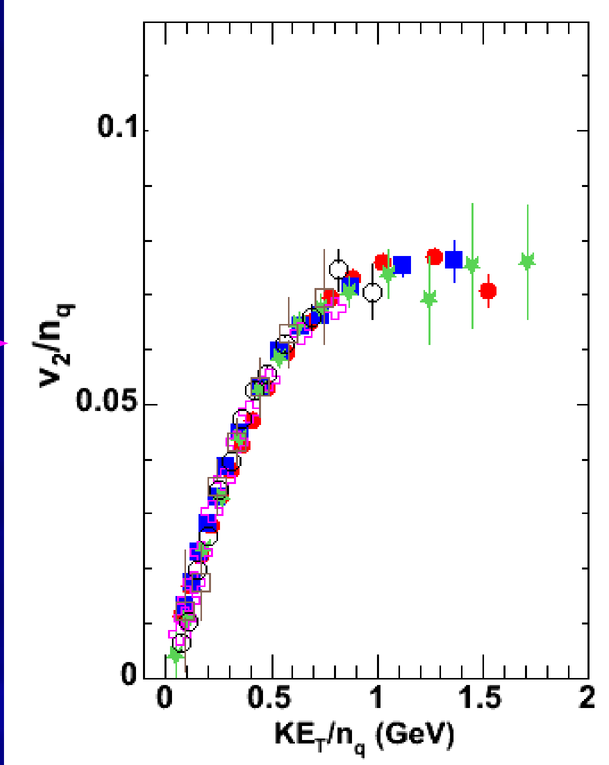


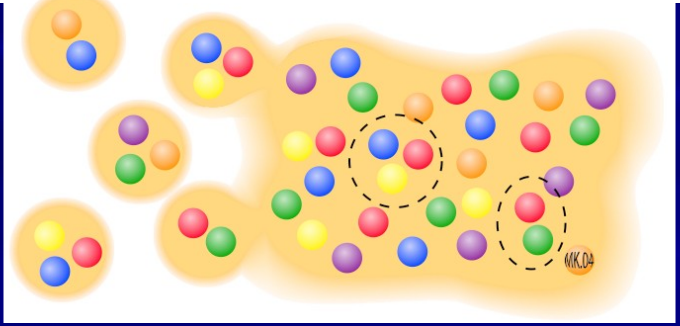
Baryons

Mesons

PHENIX preliminary

$$KE_T = m(\gamma_T - 1)$$





Quark recombination into hadrons ?

Quark degrees of freedom?

Recombination at LHC(?)

- Normal particle production in jets is fragmentation
- Recombination allows the many partons from different quarks to recombine! $p = \sum p_{partons}$ (Baryon p > Meson p)
- Njets increases at LHC => recombination region should change. Hwa and Yang (R.C. Hwa and C.B. Yang, Phys. Rev. Lett. **97**, 042301 (2006).) predicts p/π~10 out to p_T~20GeV/c with no associated jet structure!